IMPACTS OF BLACK CARBON AND ALBEDO ON BIOFUEL CLIMATE EFFECTS

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Black carbon and primary organic carbon

- Black carbon (BC) and primary organic carbon (POC)
  - **Absorbing** carbon and a mixture of organic carbon compounds, formed via **incomplete combustion**
  - Constituents of **$PM_{2.5}$ emissions**
  - Both BC and POC are **short-lived climate forcers** with atmospheric lifetimes of **days to weeks** in the lower troposphere

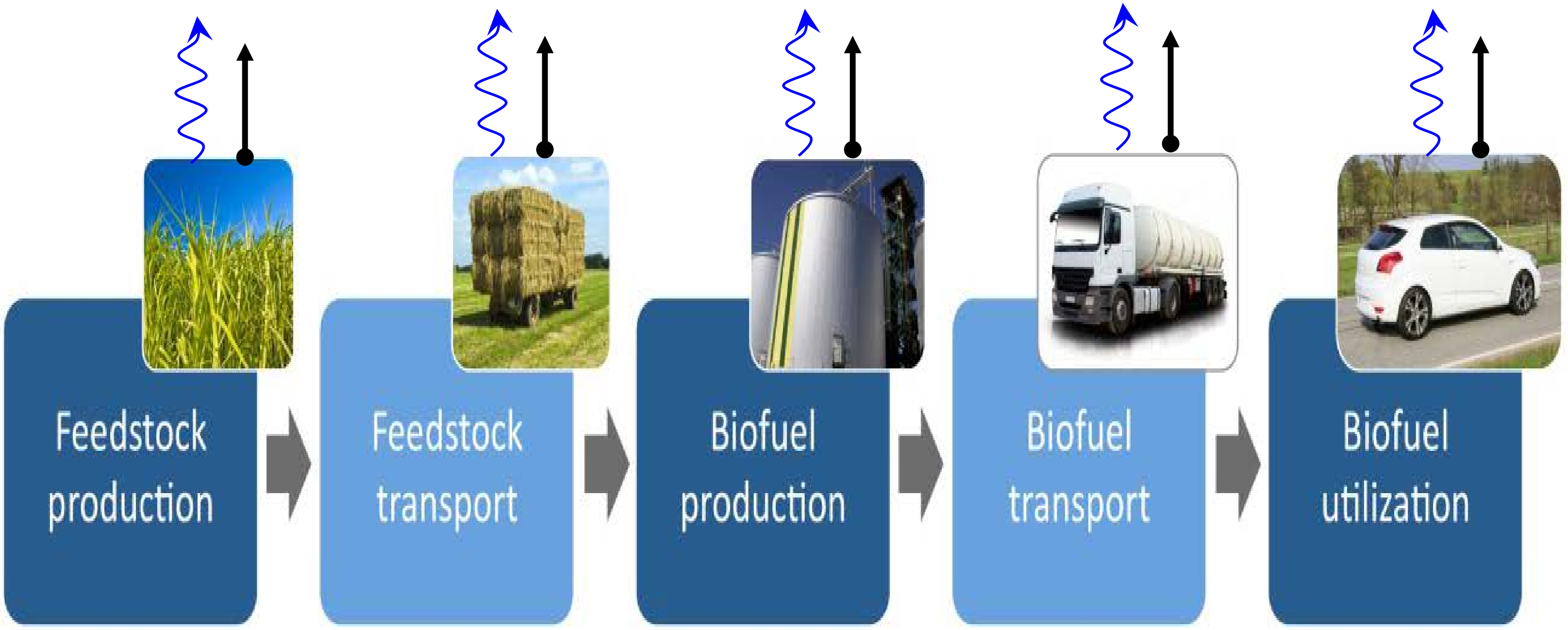
- Major emission sources of BC are on-road and off-road diesel vehicles, biomass open burning, among others in the U.S. and many parts of the world

BC and POC emissions have recently been considered in biofuel LCA with the GREET model

- **Motivation**
  - ✓ BC is the **second strongest** climate forcer after CO_2 and is the most strongly light-absorbing component of PM emissions, as indicated by a GWP_{100} of 900 and a GWP_{20} of 3200 (IPCC 2014)
  - Despite their widely recognized climate impacts, **BC and POC emissions have generally been overlooked in traditional life-cycle analysis that focuses on long-lived climate forcers**

- **Objective**
  - ✓ **To evaluate their impacts on the life-cycle GHG emissions of vehicle/fuel systems with an expanded version of the GREET™ model**

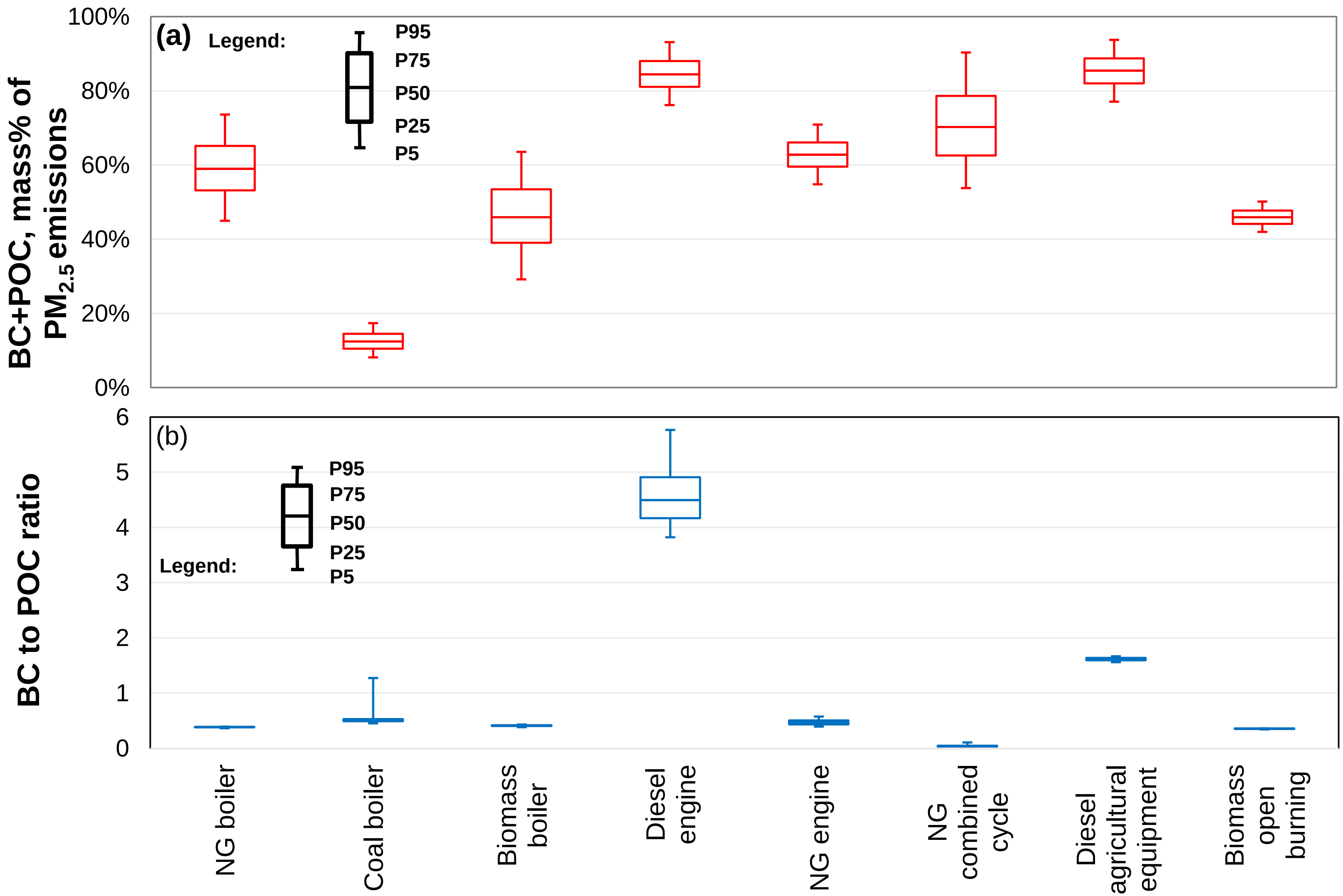
Biofuel LCA integrated with BC/POC impact analysis



System boundary of biofuel LCA integrated with BC/POC impacts

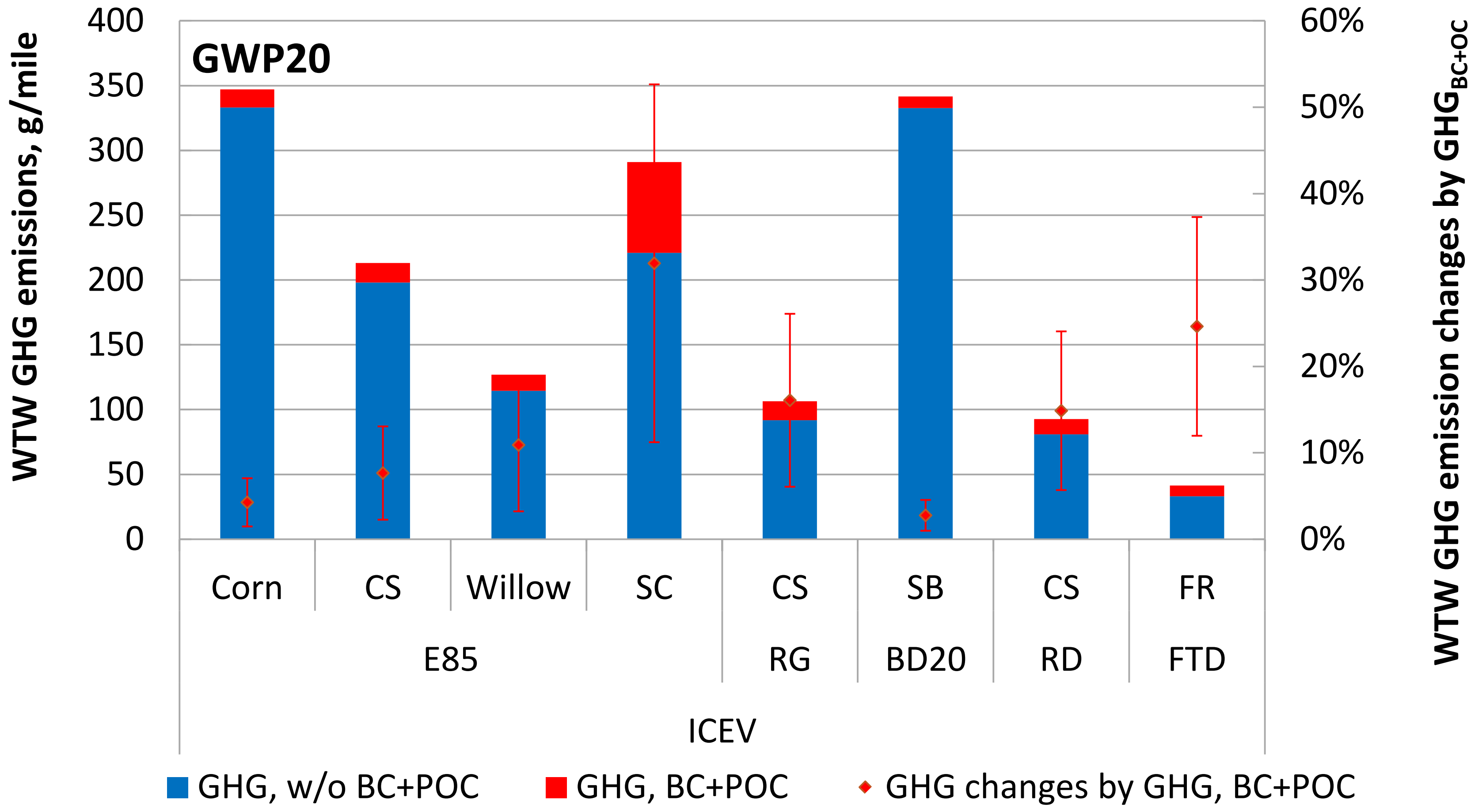
Legend: : Long-lived GHG emissions; : BC and POC emissions

Emission sources vary significantly in BC and POC emission characteristics



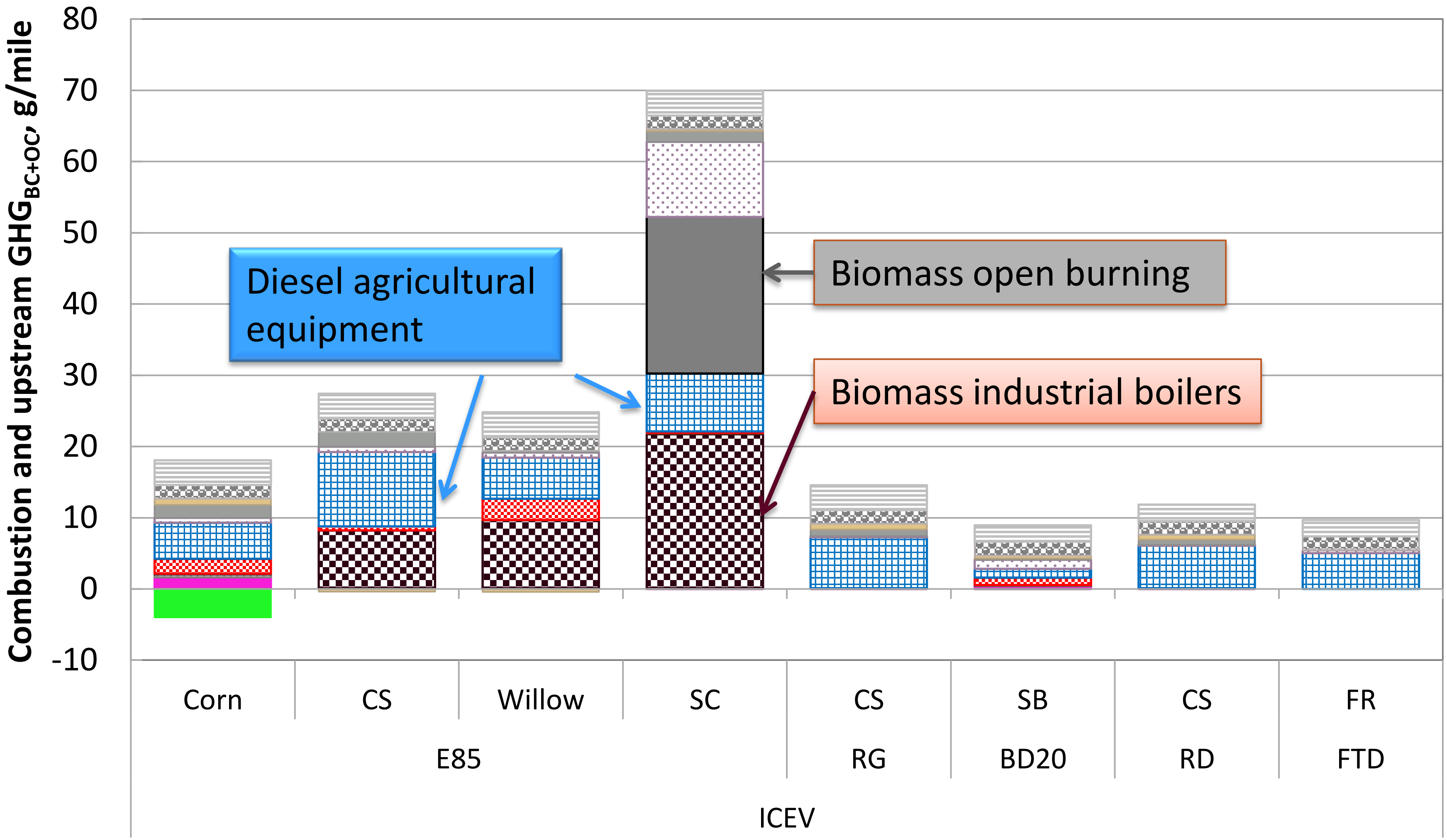
Cai and Wang, 2014

BC and POC have significant impacts on Brazilian sugarcane ethanol-fueled E85 FFVs



BC and POC contribute to **~3% - 30%** of the GHG emissions of selected biofuels

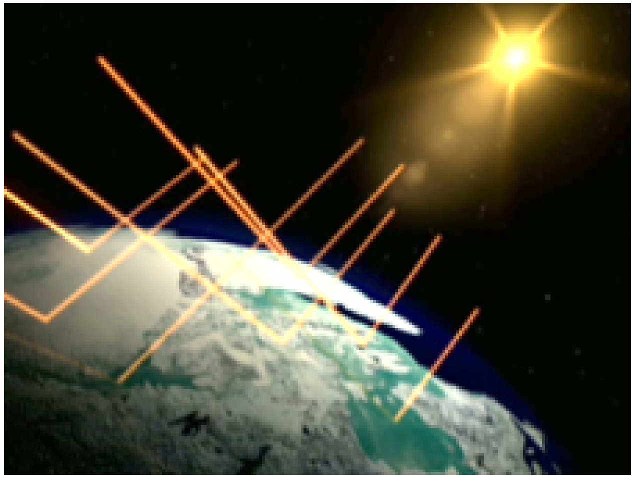
Diesel farming equipment, biomass boiler, and biomass open burning are the major emission contributors to sugarcane and cellulosic ethanol-fueled vehicles



Cai and Wang, 2014

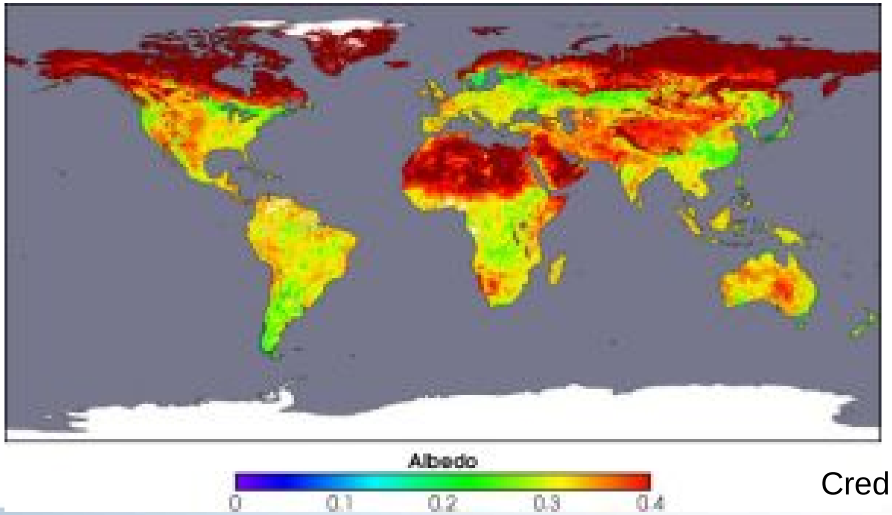
Albedo

- Albedo: A measure of how much solar radiation is reflected from Earth's surface



Credit: NASA Goddard Space Flight Center

- Albedo is spatially variable: dependent on solar zenith angle and surface land cover



Credit: NASA

The albedo effect of biofuel production is generally overlooked and could be substantial

- Biofuel production can induce land use change (LUC)
  - LUC leads to biogeochemical and biogeophysical effects

- Estimates of biofuel LUC GHG emissions are based mainly on carbon stock changes and do not include effects of changes in biogeophysical processes

- Albedo is the dominant biogeophysical effect associated with bioenergy production, particularly in areas affected by seasonal snow cover
  - Studies in literature have attempted to estimate both land use and land use change-induced albedo effects for biofuel production systems
    - Cherubini et al. (2012) focused on the albedo effect of land use (forest land)
    - MIT focused on LUC-induced albedo change by scenario analysis, with a focus on mid-distillate fuels (Caiazzo et al., 2014)

Objective: Quantification of LUC-induced albedo effects of biofuel production in the U.S.

Any cooling or warming effect?

LUC

Photo credit: P.F. Dunn

Methodology

Biofuel Production

Land Use Change (LUC)

Land Cover A	Land Cover B

Temporal Albedo Change

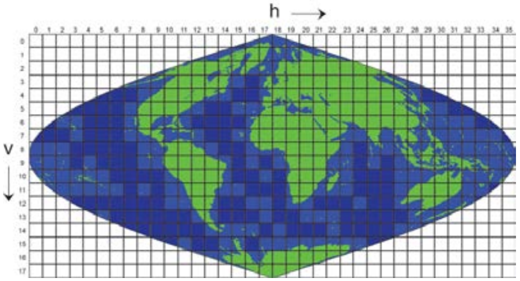
Albedo Dynamics Over Land Cover A	Albedo Dynamics Over Land Cover B

Albedo Radiation Effect

Radiation Over Land Cover A	Radiation Over Land Cover B

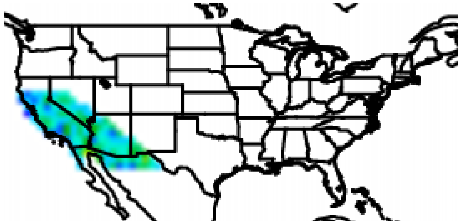
LUC-Induced Radiative Forcing

GWP-base CO_2e Emissions for the Albedo Effect

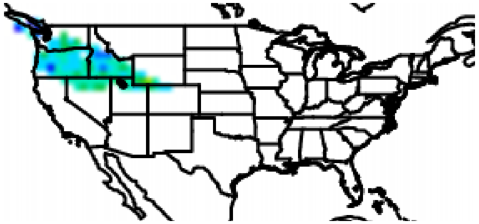


MODIS albedo data used : 9 tiles

H08V05



H09V04



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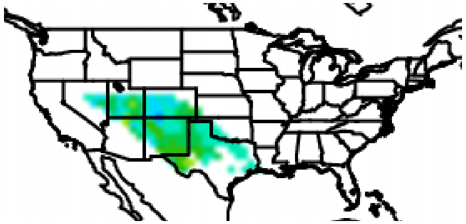
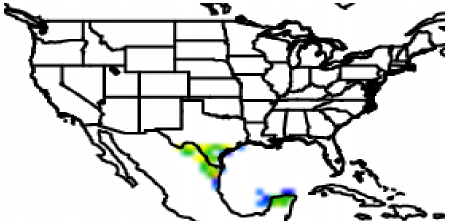
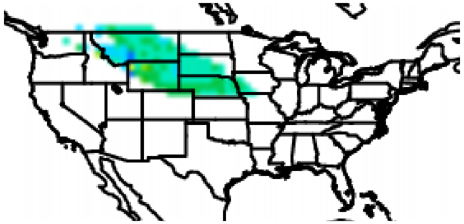


H09V06



H10V04



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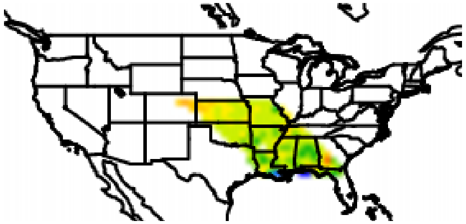

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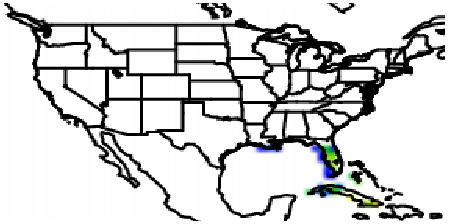
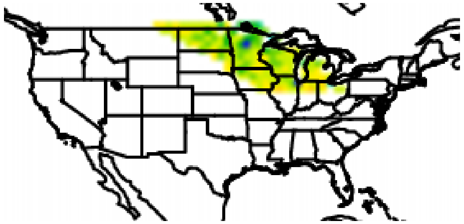
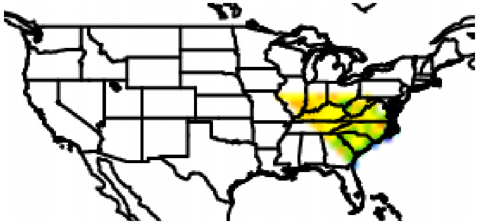


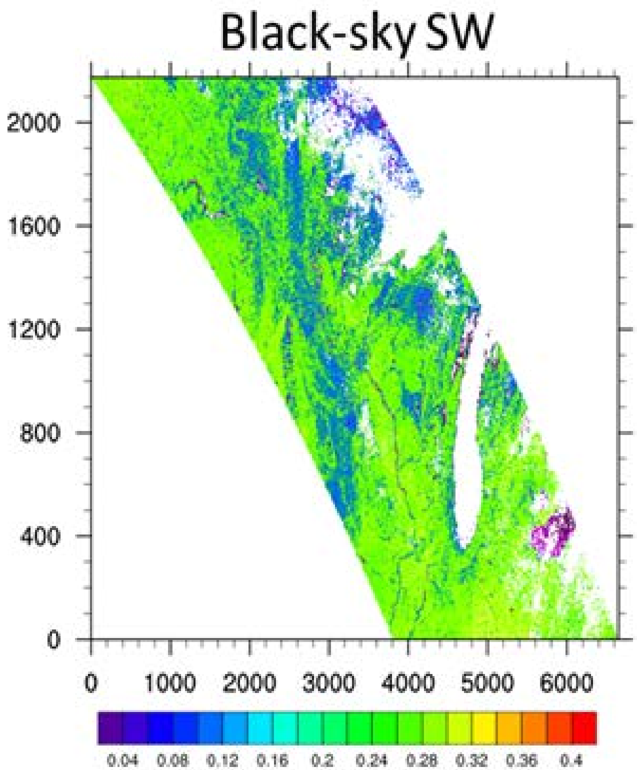
H11V04

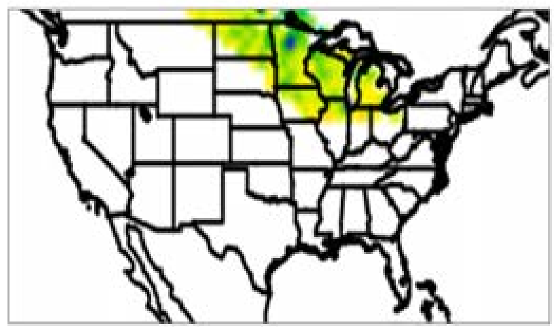


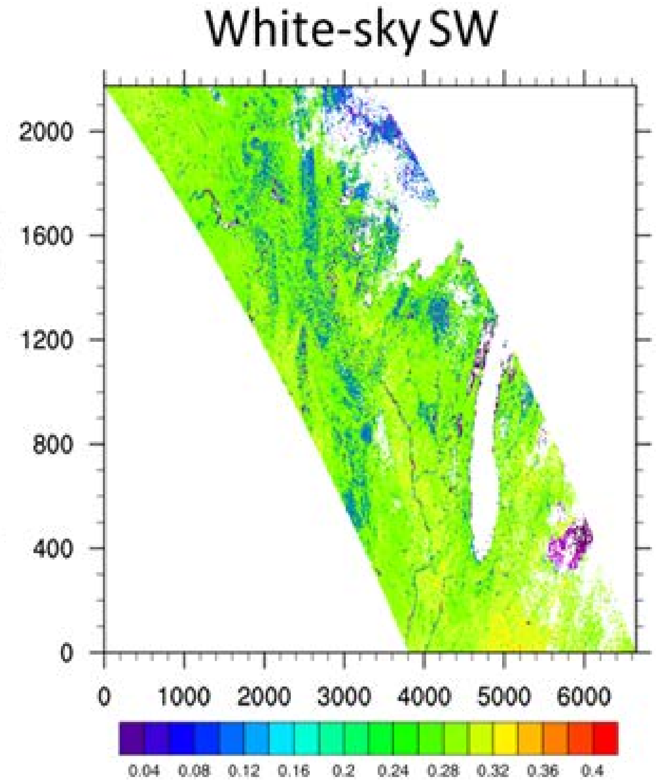
H11V05



MODIS albedo data: over 5.7 million 500×500 m pixels in one tile



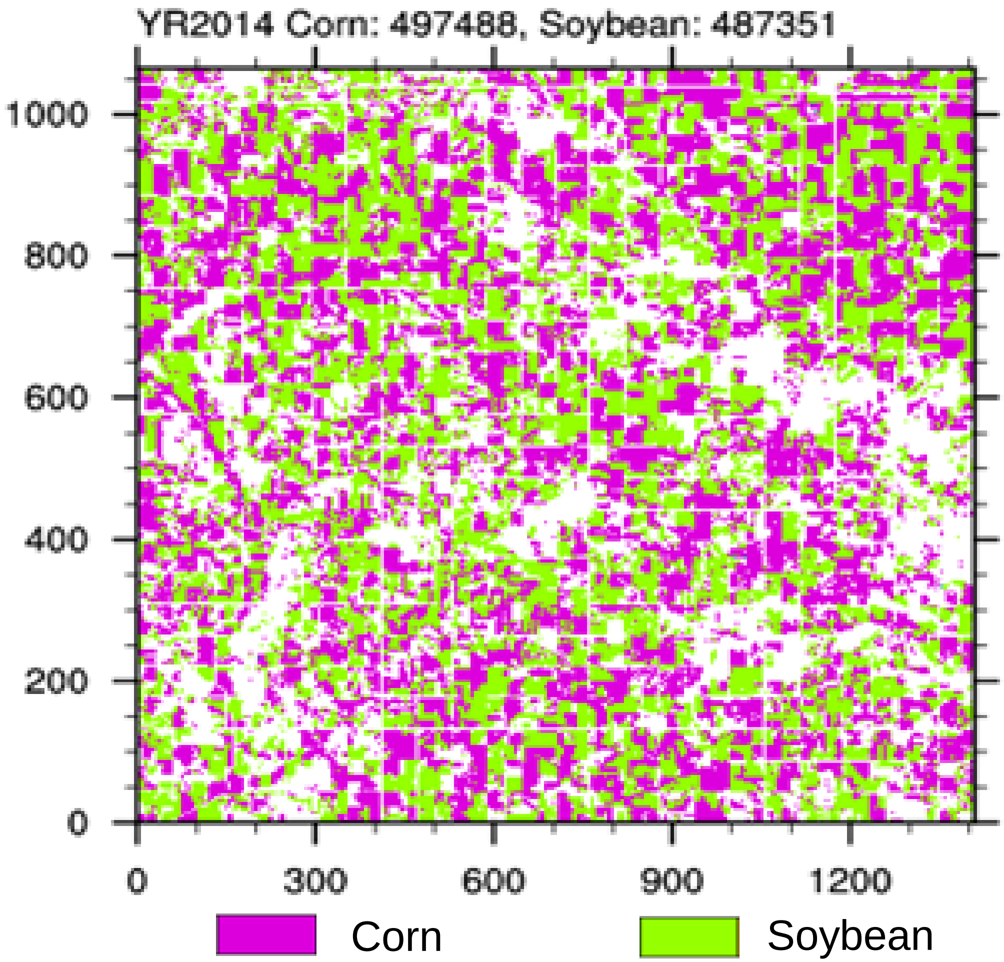




Tile H09V04 of the MCD43A3 albedo data product covering part of the U.S. Midwest

- ➢ BSA and WSA data represent two extreme cases and are both available

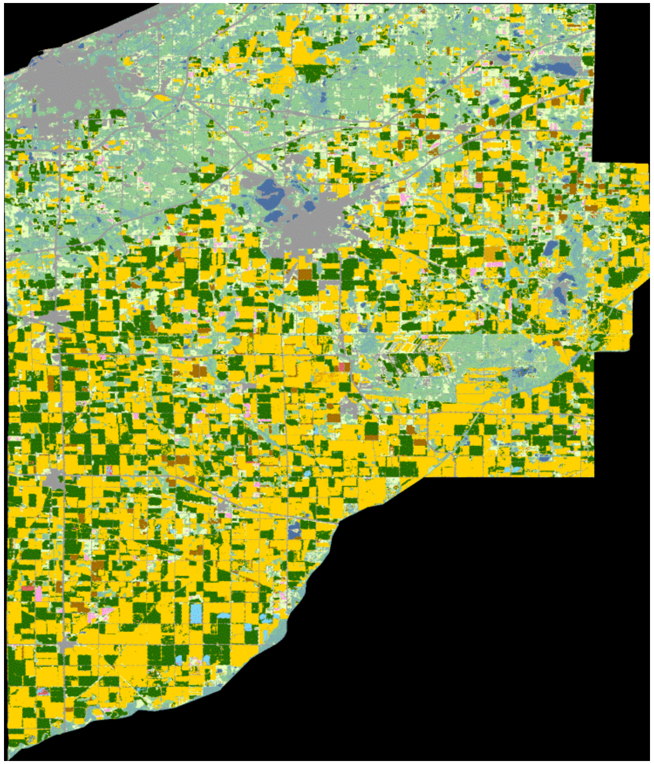
High spatial resolution land cover data is used to identify land cover types

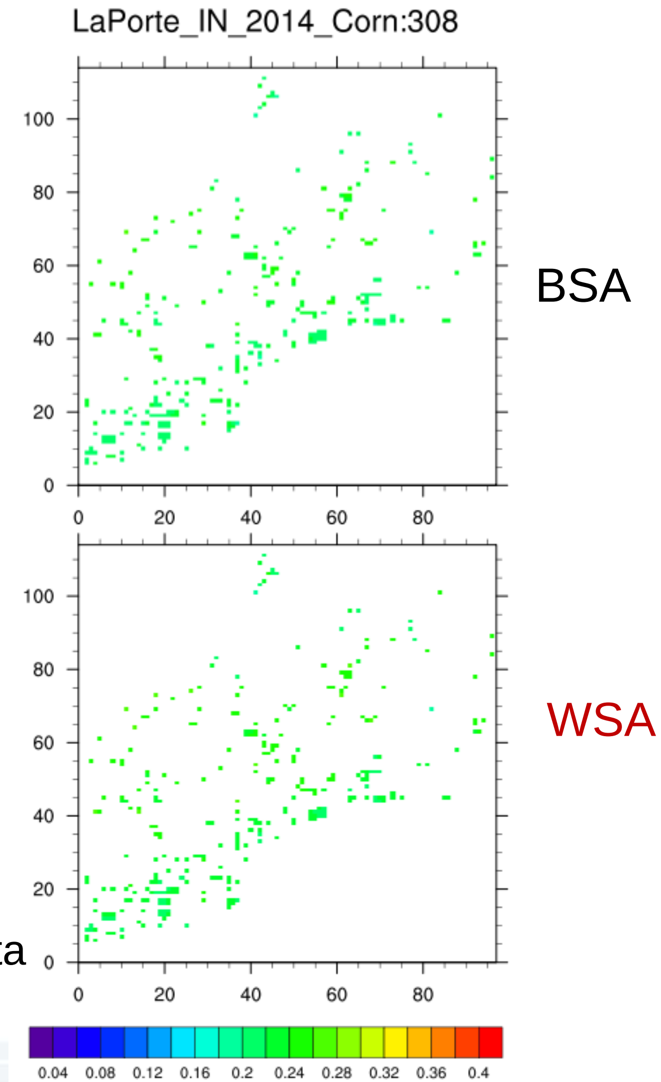


Adair County, Iowa, 2014

- **USDA Cropland Data Layer (CDL)**
  - A geospatial satellite data product
  - Covers CONUS since 2008
  - Up to 175 land cover types, including cropland, e.g., corn, soybean, sorghum, wetland, forest, and vegetables/fruits
  - Available at county level
  - High resolution, 30 meters
  - GeoTIFF format

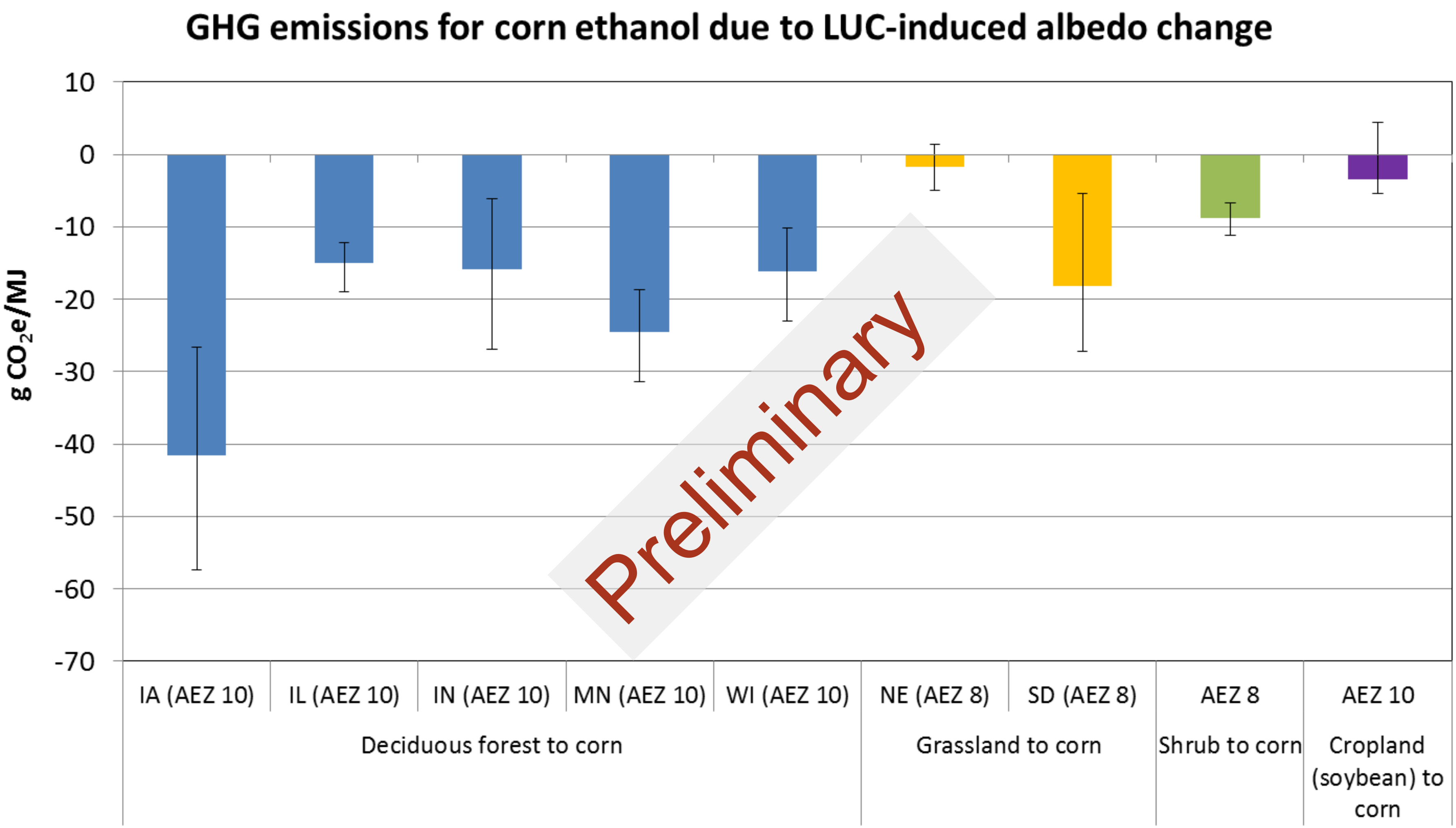
Geospatial analysis techniques overcome barriers to pairing albedo and land cover data geographically in search of “clean pixels”



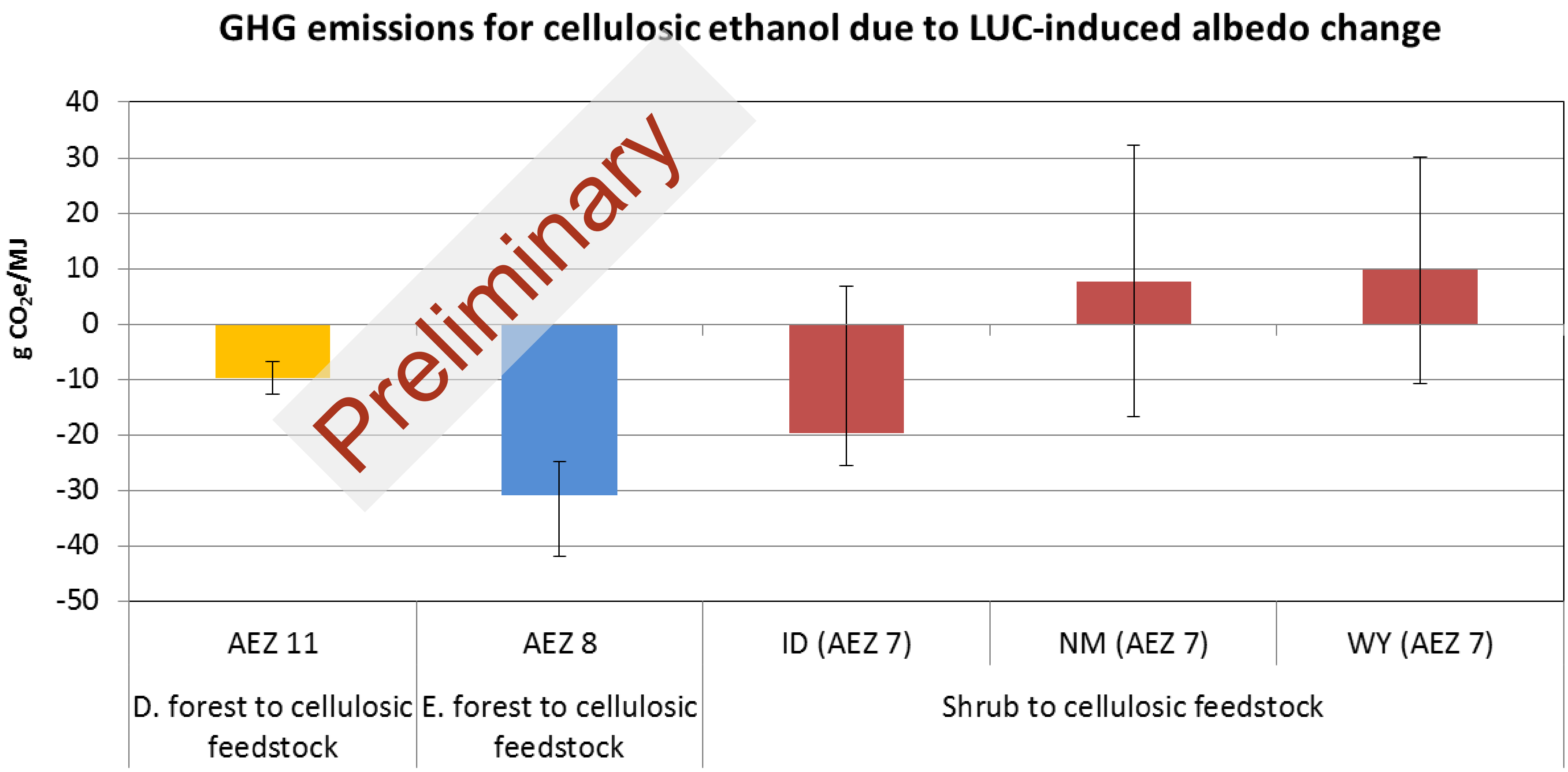


Land cover (~30 m) ➔ Land cover (~500 m) ➔Pairing
➔ Threshold of “Clean Pixels”:100% ➔ Retrieve albedo data

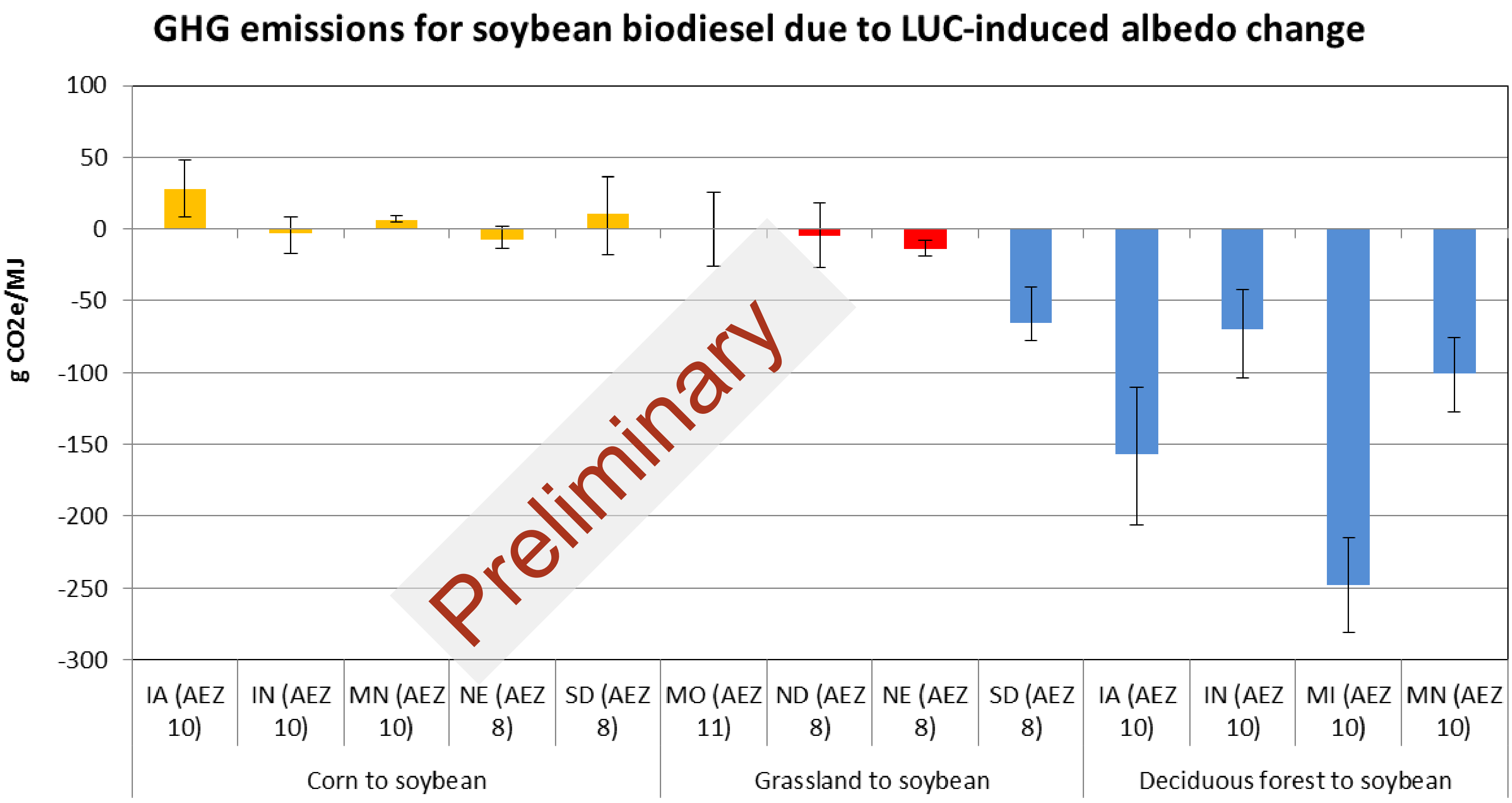
Corn ethanol: albedo effects for "what-if" LUC scenarios



Cellulosic ethanol: albedo effects for "what-if" LUC scenarios



Soybean biodiesel: albedo effects for "what-if" LUC scenarios



Summary

- **BC Effect:**
  - BC emissions can be important for biofuel production pathways that combust diesel, combust biomass in the open field, or operate biomass boilers intensively
- **Albedo Effect:**
  - Scenario analysis shows that albedo effect is highly variable among different LUC scenarios
  - Spatial variability of the albedo effect is another important aspect to address for integration of this metric into biofuel LCA framework
  - ANL is continuing the albedo work to address these issues

Acknowledgment

- Both BC/POC and albedo studies are funded by Bioenergy Technologies Office of the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy. We thank Alicia Lindauer of that office for her support and guidance.

ANL documentation

- For more details on BC and OC emission factors and the analysis are documented in an ANL Technical Report: https://greet.es.anl.gov/publication-black-carbon-greet and in an ES&T paper: http://pubs.acs.org/doi/pdf/10.1021/es503852u

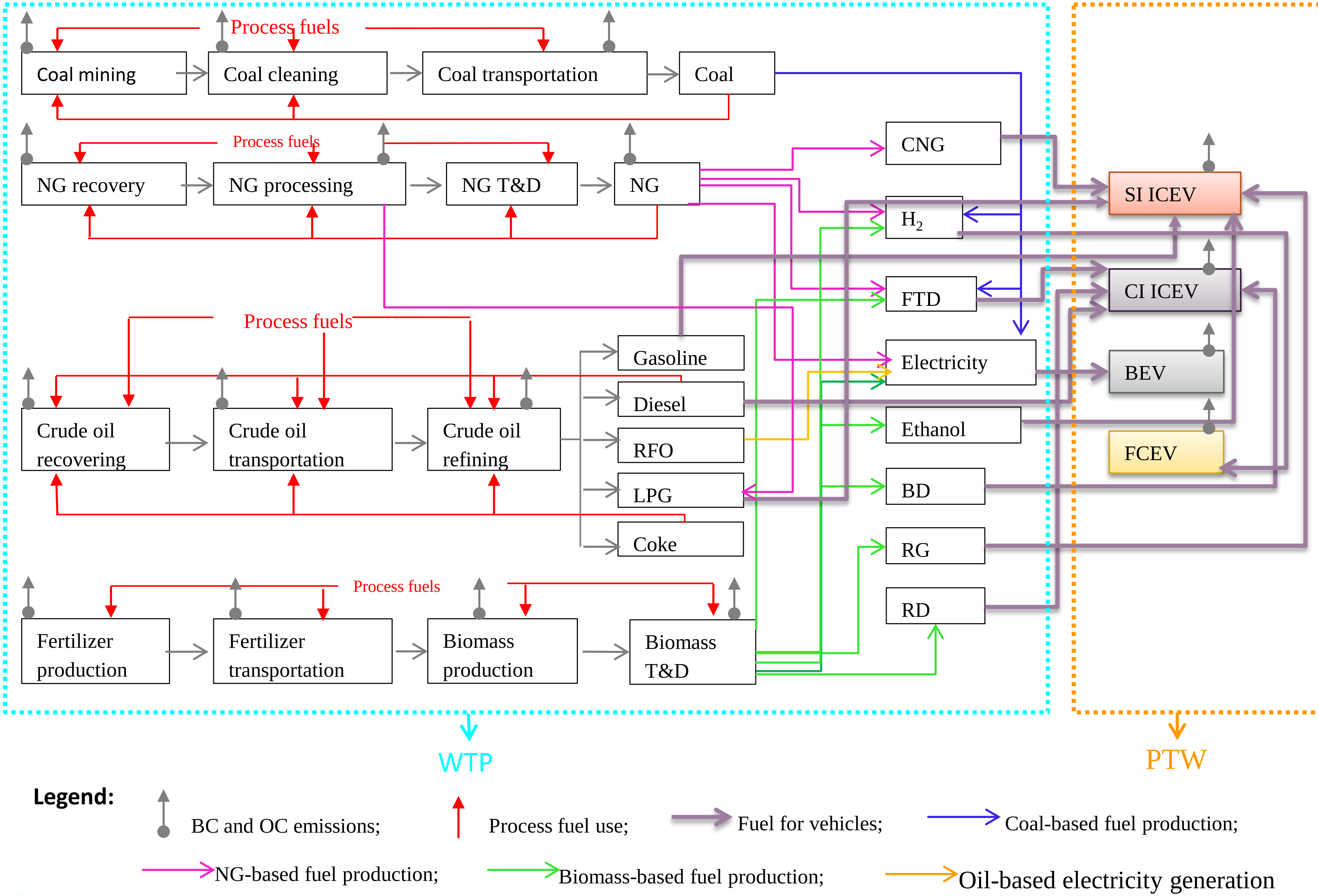
- An ANL documentation of the albedo study is forthcoming

Thanks!

Questions/Comments?

Back-Up Slides

Incorporating BC&POC into LCA: System Boundary



Cai and Wang, 2014

Baseline gasoline and diesel vehicles and a large variety of vehicle/fuel systems are evaluated

Vehicle technologies	Fuel and feedstock options
SI ICEVs	90% petroleum gasoline with 10% corn ethanol by volume
	RG: CS via pyrolysis
	RG: FR via pyrolysis
	CNG: conventional and shale NG
	LPG: NG and petroleum
CIDI ICEVs	Petroleum LSD
	BD20: SB
	RD: CS via pyrolysis
	RD: FR via pyrolysis
	FTD: NG
	FTD: coal
	FTD: FR
SI FFVs	E85: 85% corn ethanol and 15% petroleum gasoline by volume
	E85: 85% CS ethanol and 15% petroleum gasoline by volume
	E85: 85% willow ethanol and 15% petroleum gasoline by volume
	E85: 85% SC ethanol and 15% petroleum gasoline by volume
	E85: 85% SS ethanol and 15% petroleum gasoline by volume
SI ICE HEVs	90% petroleum gasoline with 10% corn ethanol by volume
SI ICE PHEV40s	90% petroleum gasoline with 10% corn ethanol by volume, and U.S. mix electricity
BEV100s	Electricity: U.S. mix
	Electricity: CA mix
FCEVs	Hydrogen: NG
	Hydrogen: coal
	Hydrogen: poplar
	Hydrogen: WE with U.S. average grid

Cai and Wang, 2014

BC and OC emission factors are key to WTW BC and OC emission estimation

$$WTW_{CF_s} = \left\{ \sum_p \sum_i \sum_j \left[(\frac{1}{\eta_p} - 1) \times PF_{p,i} \times CT_{p,i,j} \times EF_{CF_s,i,j} \right] + \sum_p \sum_i \left[Upstream_{CF_s,i} \times (\frac{1}{\eta_p} - 1) \times PF_{p,i} \right] \right\}$$

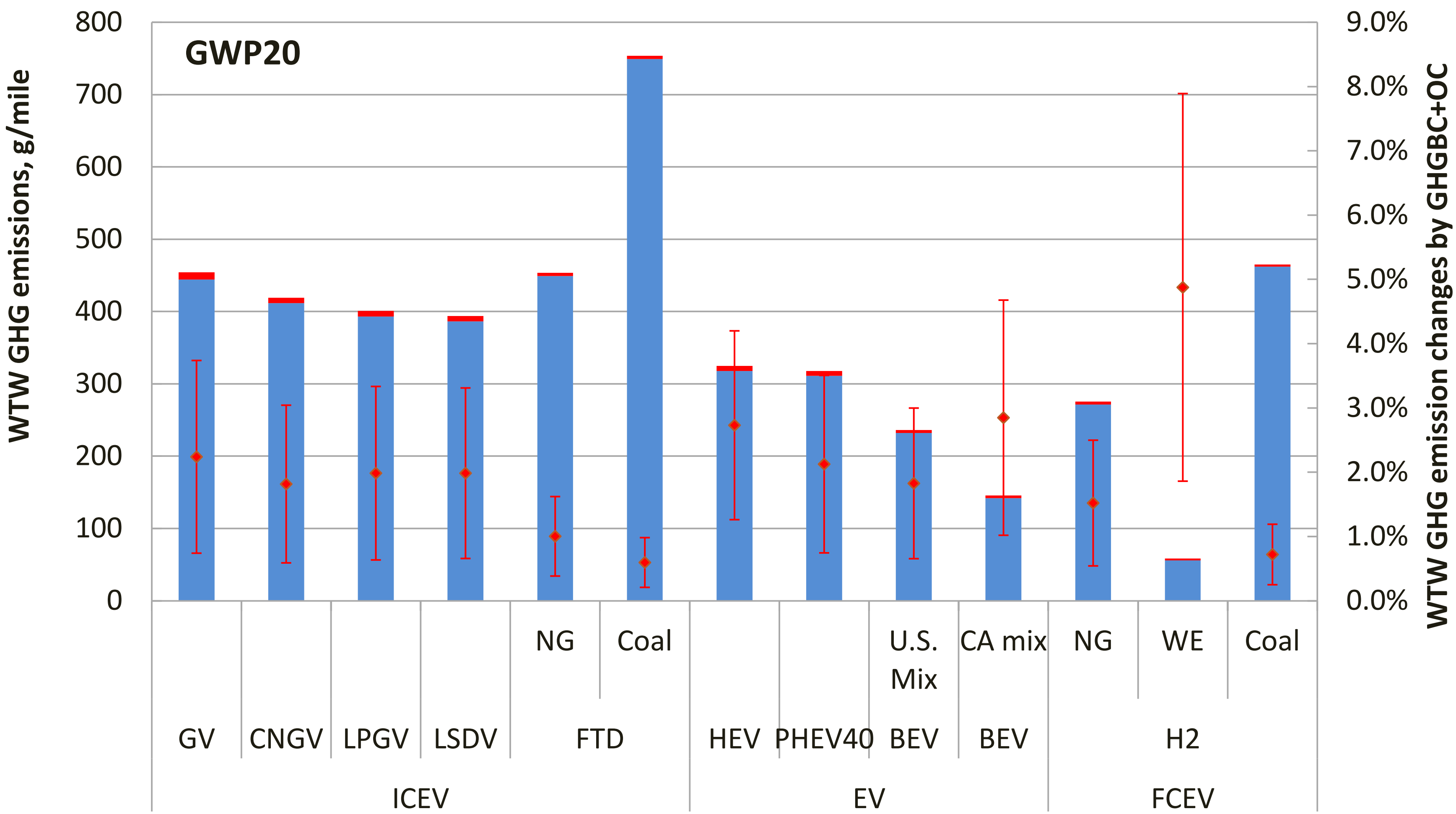
$$\times \frac{GGE}{MPGGE} + VO_{T,CF_s} + VO_{TBW,CF_s}$$

$$EF_{BC,i,j} = EF_{PM_{2.5},i,j} \times MF_{BC,i,j} \qquad EF_{OC,i,j} = EF_{PM_{2.5},i,j} \times MF_{OC,i,j}$$

$$GHG_{BC,i,j} = WTW_{BC,i,j} \times GWP_{BC} \qquad GHG_{OC,i,j} = WTW_{OC,i,j} \times GWP_{OC}$$

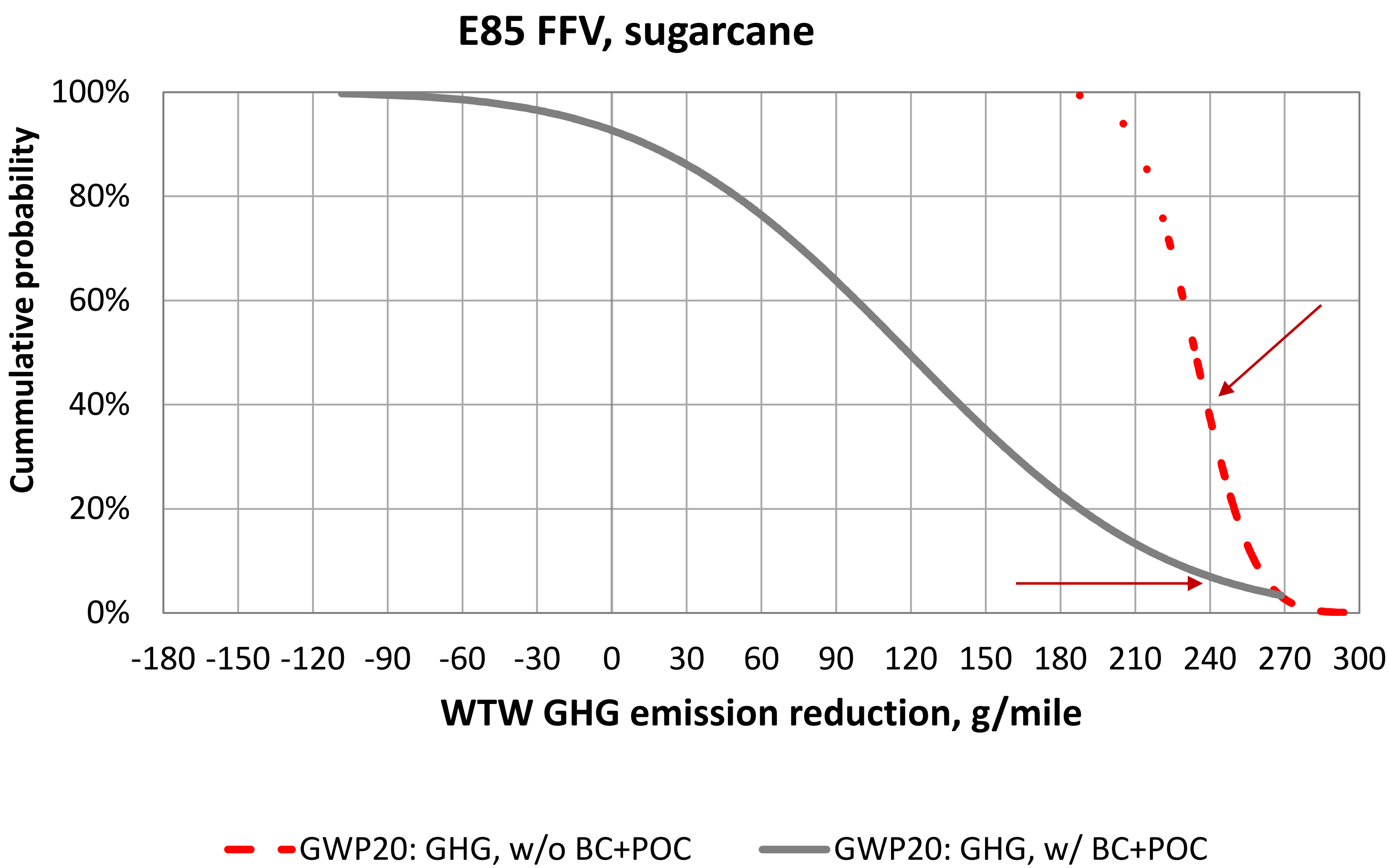
- **A combustion technology-based $PM_{2.5}$ emission factors are estimated**
  - **Power sector**: EIA utility-level databases and EPA's continuous emission monitoring systems and AP-42
  - **Other stationary** emission sources: primarily based on the EPA's AP-42 compilation of emission factors, on the types and scales of emission control technologies deployed, and on current emission regulations
  - **Mobile** sources: MOVES and NONROAD simulations and open literature
  - **Open combustion** sources: literature review
- **Literature-based compilation of $PM_{2.5}$ emission source profiles**
  - EPA's SPECIATE and CARB PM source profile databases
  - Open literature

Small impacts of BC and OC emissions on fossil- and electricity-powered vehicle systems



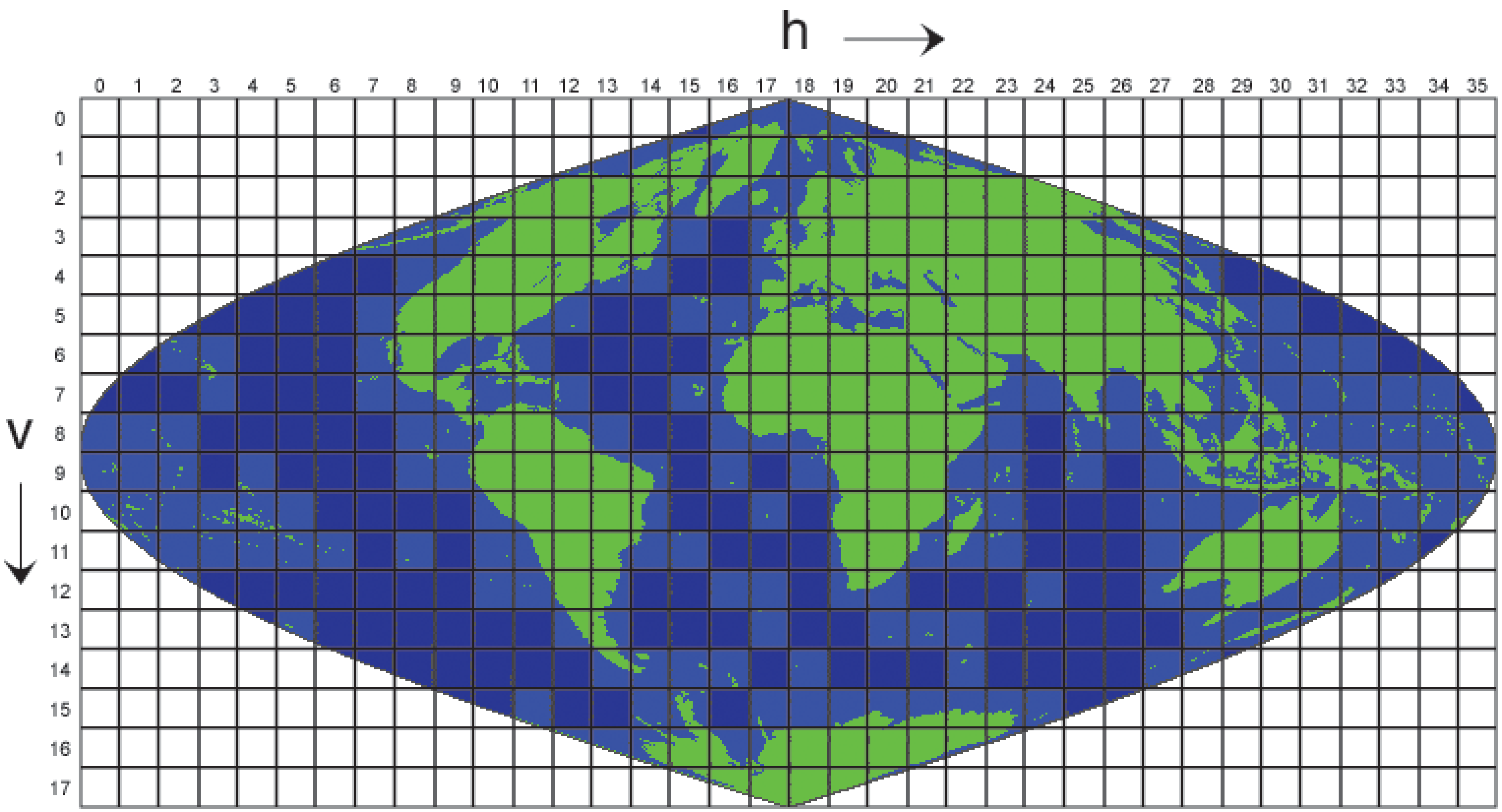
Cai and Wang, 2014

BC and POC emissions significantly reduce the probabilities for bioethanol-fueled FFVs to achieve a given level of WTW GHG emission reduction



Cai and Wang, 2014

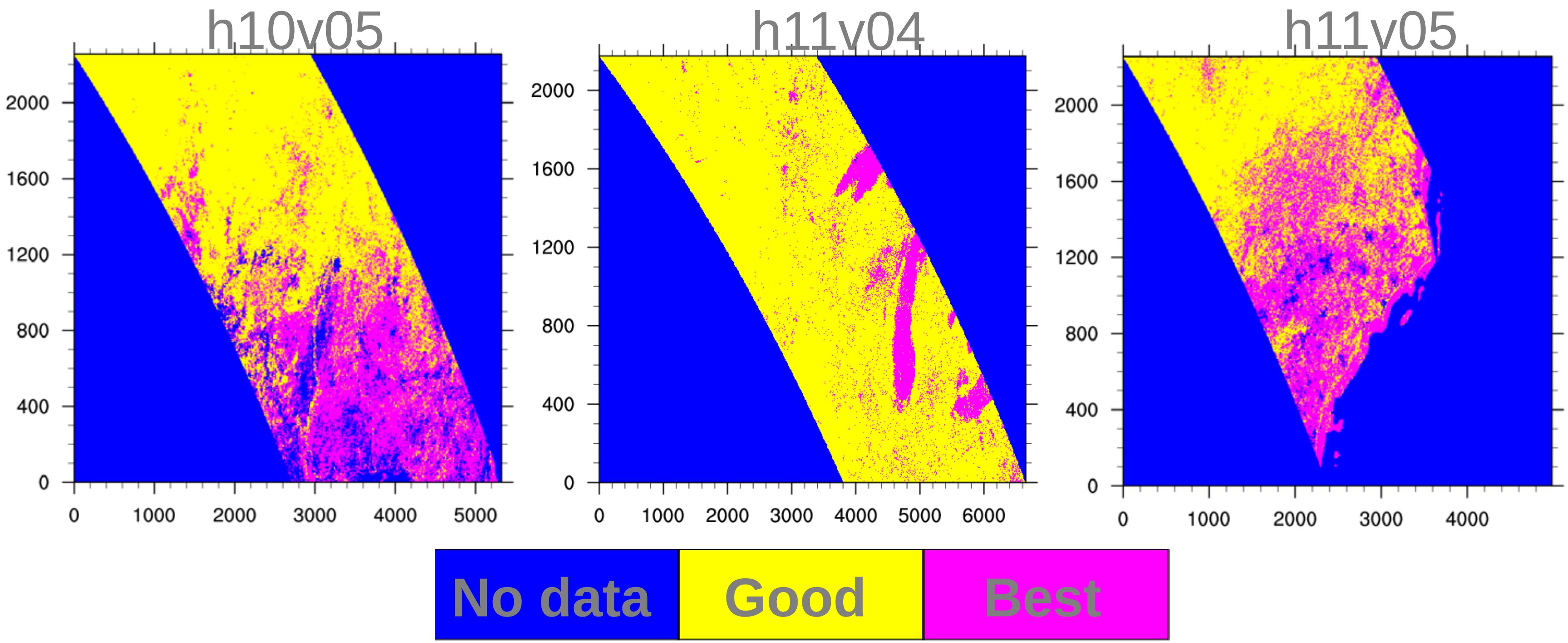
MODIS MCD43A3 Albedo Data Product over the Global



MODIS Albedo Products

- ✓ Produced in 10˚ by 10˚ (1200 km by 1200 km) tiles on a 500 m by 500 m sinusoidal grid
  - ✓ 648 tiles over the entire global land surface
  - ✓ Ten tiles covers most of the CONUS
- ✓ Saved in the Hierarchical Data Format (HDF)

MODIS Albedo Data Is of High Quality



- Most data are of good or best quality

Satellite Remote Sensing Is the Widely Adopted Approach For Obtaining Albedo Data

- Empirical approaches are primarily employed for the determination of albedo
  - Including remote sensing and in situ measurements

Albedo Data Sets	Input Source	Spatial Resolution	Frequency	Temporal Coverage	Type of Albedo
MODIS	**MODIS**	**0.05°**	**8 day**	**2000 to present**	**BSA and WSA**
GLASS	AVHRR and MODIS	0.05°	8 day	1981 to present	BSA and WSA
GlobAlbedo	AATSR, MERIS, VGT, and MODIS	0.05°	Monthly	1998–2011	BSA and WSA
MERIS	MERIS	0.25°	Monthly	2002–2006	BSA
CLARA-SAL	AVHRR	0.25°	10 day and Monthly	1982–2009	BSA
ERBE	ERBE	2.5°	Monthly	1985–1989	BSA
GEWEX		1°		1983–2007	
ISCCP				1983–2009	
CERES		1°		2000–2012	

He et al., 2014

Over 350,000 Clean Pixels Albedo Data for Multiple Land Cover Types In Various Counties Are Retrieved Every Eight Days Through 2014

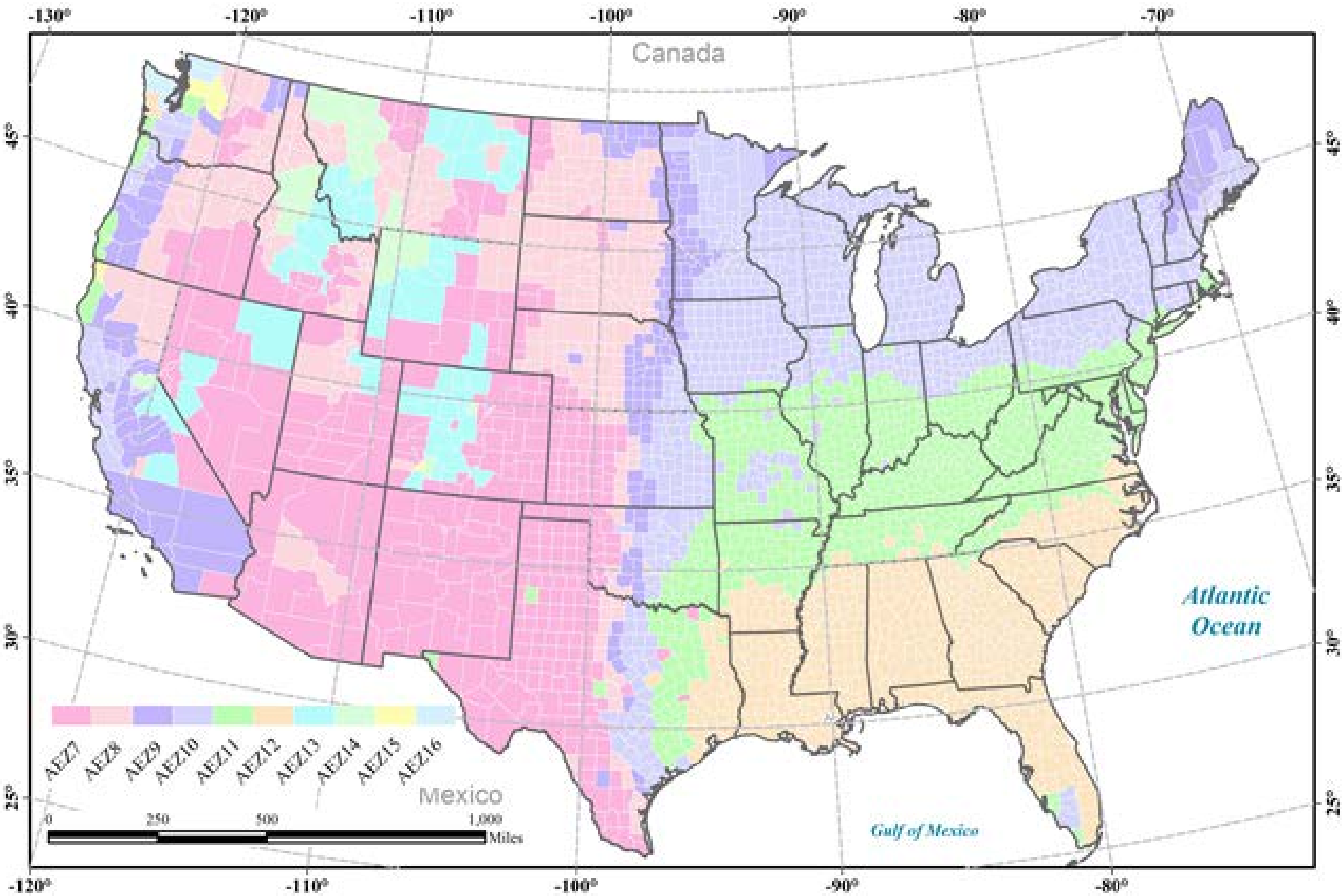
Land cover	State	Number of clean pixels	Land cover	State	Number of clean pixels	Land cover	State	Number of clean pixels
Canola	KS	11	Evergreen Forest	OR	3236	Sorghum	TX	2478
Canola	ND	319	Evergreen Forest	SC	234	Soybean	AR	1466
Corn	IA	4884	Evergreen Forest	VT	2564	Soybean	IA	250
Corn	IL	2836	Evergreen Forest	WA	1141	Soybean	IL	284
Corn	IN	2102	Grass	CA	678	Soybean	IN	135
Corn	MN	3271	Grass	CO	15804	Soybean	LA	300
Corn	NE	1718	Grass	ID	580	Soybean	MI	60
Corn	SD	811	Grass	KS	3570	Soybean	MN	2636
Corn	WI	367	Grass	MO	81	Soybean	MO	896
Cotton	TX	22973	Grass	MT	12177	Soybean	ND	1255
Deciduous Forest	GA	2702	Grass	ND	2378	Soybean	NE	526
Deciduous Forest	IA	4	Grass	NE	33154	Soybean	OH	363
Deciduous Forest	IL	60	Grass	NM	24796	Soybean	SD	785
Deciduous Forest	IN	1190	Grass	OK	470	Sugarcane	FL	1203
Deciduous Forest	KY	1381	Grass	SD	8943	Sugarcane	LA	33
Deciduous Forest	MI	27	Grass	WY	6258	Summer Wheat	ND	486
Deciduous Forest	MN	342	Rice	AR	582	Summer Wheat	SD	133
Deciduous Forest	MO	4627	Rice	CA	1048	Wetland	FL	1094
Deciduous Forest	NC	7611	Rice	MO	35	Wetland	GA	1516
Deciduous Forest	OH	1880	Shrub	AZ	41130	Wetland	MI	4
Deciduous Forest	WI	164	Shrub	ID	12091	Wetland	MN	2516
Deciduous Forest	WV	1881	Shrub	NM	27900	Wetland	NC	1726
Evergreen Forest	CT	1987	Shrub	NV	11477	Winter Wheat	KS	3067
Evergreen Forest	ID	430	Shrub	OR	34091	Winter Wheat	NE	181
Evergreen Forest	MA	1464	Shrub	UT	13354	Winter Wheat	OK	417
Evergreen Forest	MI	377	Shrub	WY	15317	Winter Wheat	SD	134
Evergreen Forest	MT	4955	Sorghum	KS	1425			
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]			

Radiative Forcing Modeling of the Albedo Effect

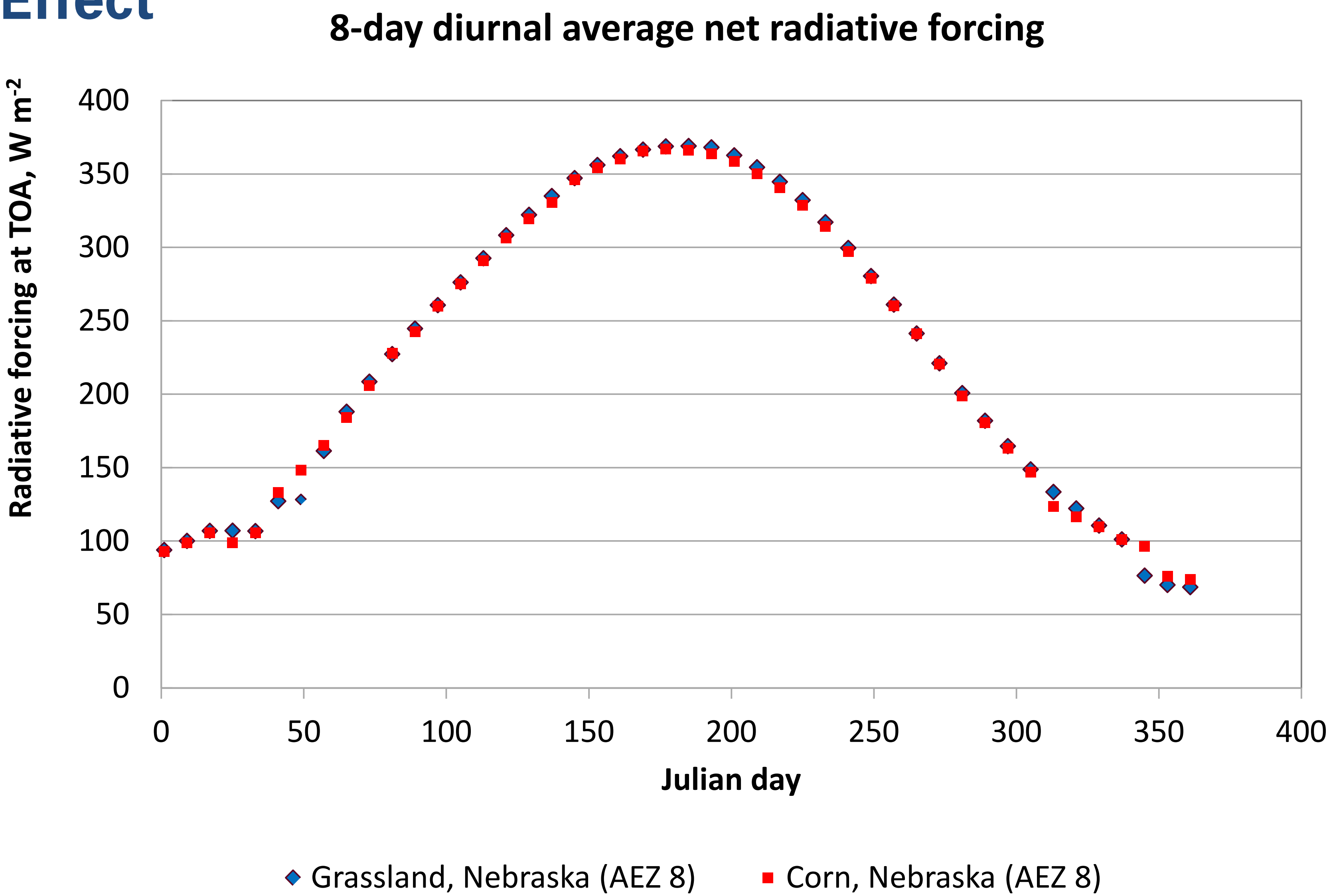
- The Monte Carlo Aerosol, Cloud and Radiation (MACR) model, a sophisticated radiative forcing modeling system, is adopted to simulate the radiative forcing of the albedo effect
  - Extensively validated (Satheesh et al., 1999; Podgorny et al., 2000; Ramanathan et al., 2001)
  - Built on advanced radiative transfer coupled with spatially and temporally resolved meteorological and aerosol conditions

- The MACR model simulations output the 8-day diurnal average net radiative forcing on the local TOA resulting from the albedo effect over each land cover type in various countries

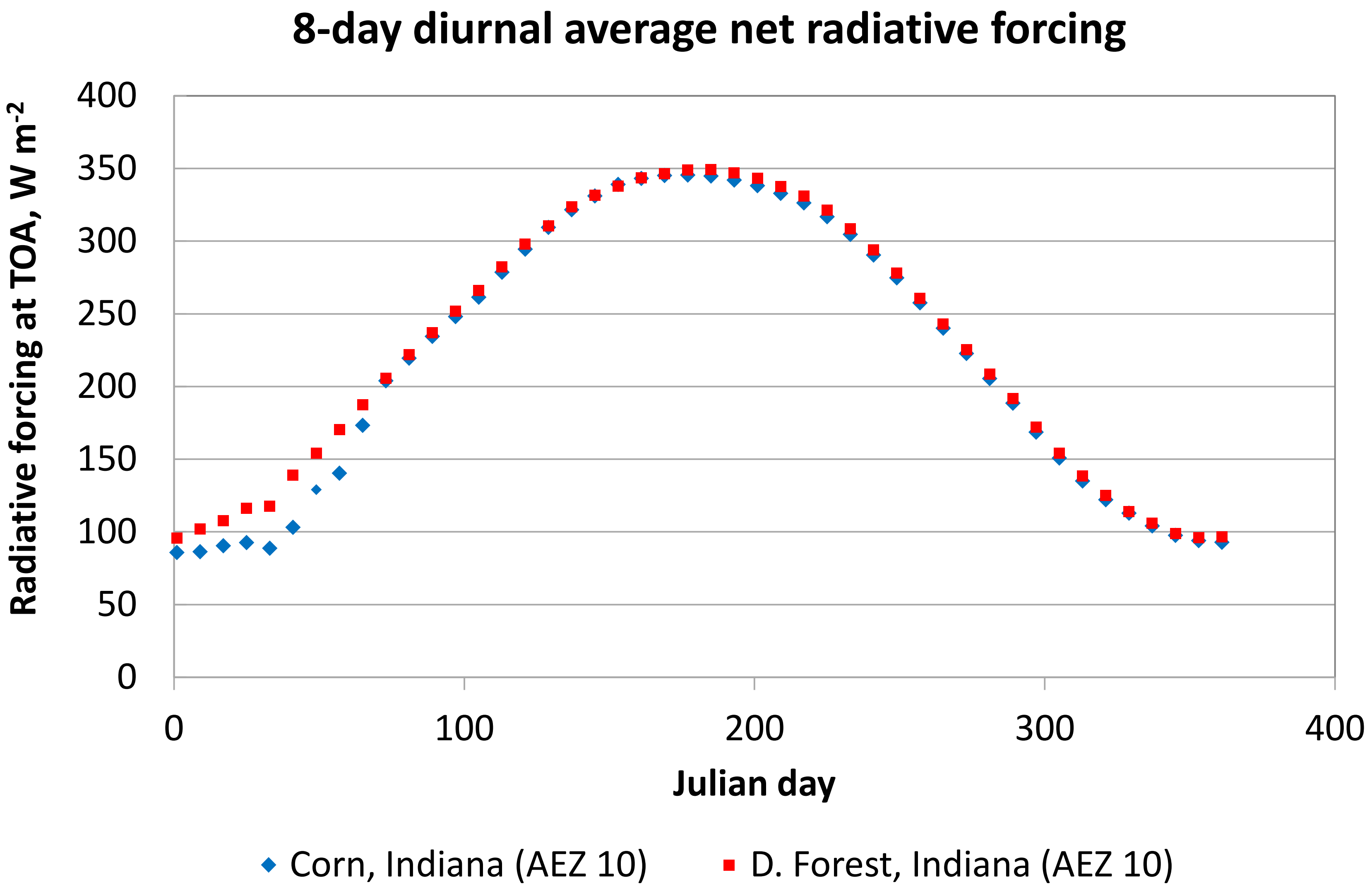
Map of AEZ in the U.S.



Model-Simulated Radiative Forcing of the Albedo Effect



Simulated Radiative Forcing of the Albedo Effect



CO_2-Equivalent Emission Conversion of Albedo Effect: The IPCC Approach

- $$CO_2e_{albedo,LUC}(H) = \frac{\Delta RF_{albedo,LUC,global}}{\int_0^H RF_{CO_2}(t)dt} = \frac{\Delta RF_{albedo,LUC}}{AGWP_{CO_2}(H)} \times \frac{A_{LUC}}{A_{Global}}$$

Where: $CO_2e_{albedo,LUC}(H)$ is the CO_2-Equivalent emission, in kg CO_2, of the LUC-induced albedo on a time horizon of *H* years; $\Delta RF_{albedo,LUC}$ is global radiative forcing, in W year/m^2, of the LUC-induced albedo change; $\Delta RF_{albedo,LUC}$ is the LUC-induced local radiative forcing, in W year/m^2; A_{LUC} is the area, in m^2, of the LUC; A_{Global} is the surface area of the Earth, and $AGWP_{CO_2}(H)$ is the Absolute Global Warming Potential of the reference gas CO_2 on a time horizon of *H* years.

- $$CO_2e_{Biofuel,albedo,LUC}(H) = \frac{CO_2e_{albedo,LUC}(H)}{Biofuel\ Yield} \times 1000$$

Where: $CO_2e_{Biofuel,albedo,LUC}(H)$ is the CO_2-Equivalent emission, in g CO_2 per MJ of biofuel for the LUC-induced albedo effect on a time horizon of *H* years; and $Biofuel\ Yield$ is the biofuel yield, in MJ, from the area of the LUC.

Sorghum Ethanol: Albedo Effects for "What-if" LUC Scenarios