Evapotranspiration from Landsat's Thermal Imager

Landsat "8" – launched Feb. 2013

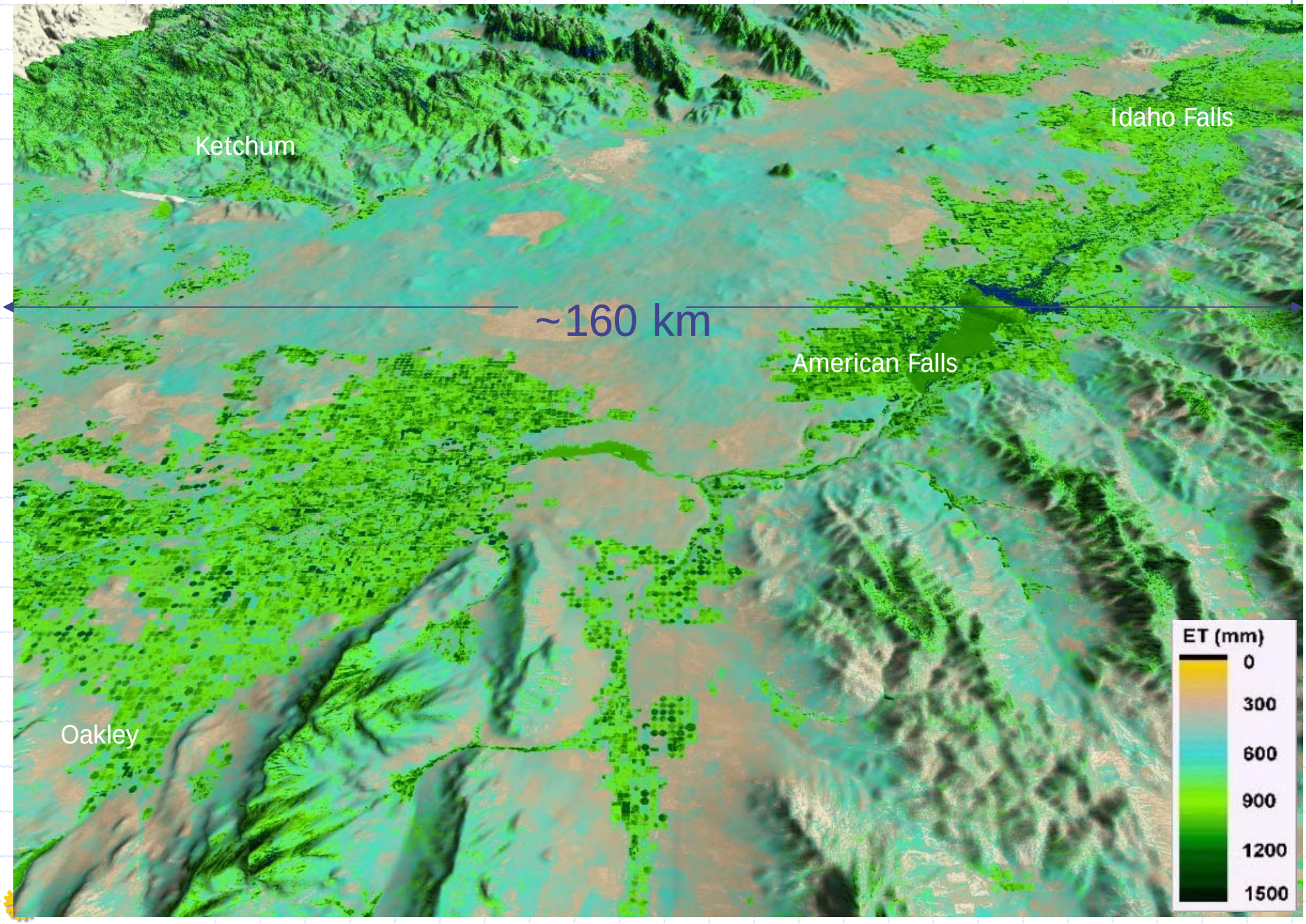
Rick Allen -- University of Idaho, Kimberly, Idaho

Professor of Water Resources Engineering
Member, USGS/NASA Landsat Science Team
Member, NASA HyspIRI Science Team

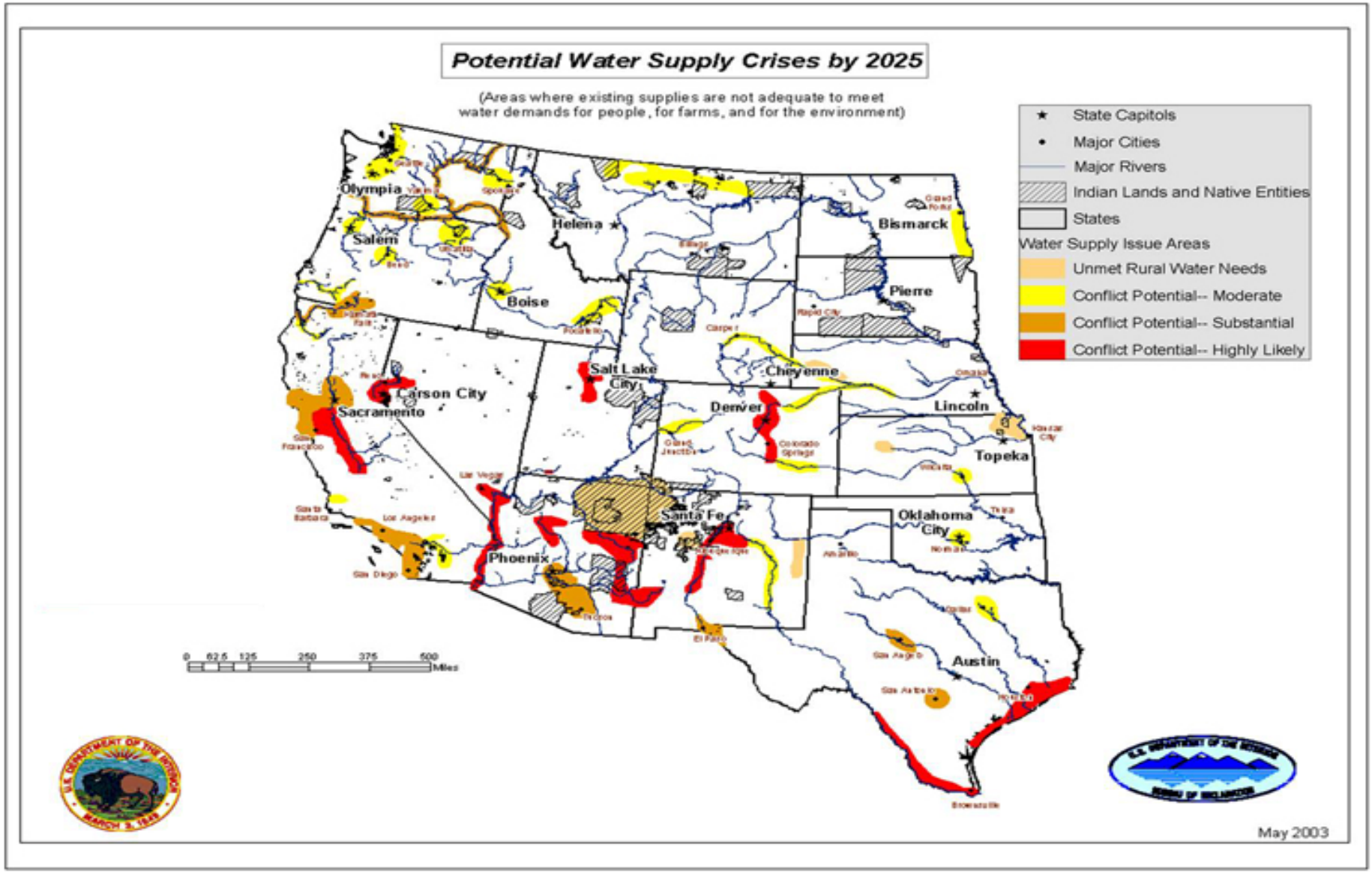
University of Idaho
A LEGACY OF LEADING

Does ET vary in Space? (Yes!) -- Monthly and Seasonal ET at 30 m resolution for the Eastern Snake Plain of Idaho

April – October, 2006 ET



Potential Water Conflicts in the West



Operational ET “mapping” using a surface energy balance – METRIC

- Mapping EvapoTranspiration with high Resolution and Internalized Calibration

Allen et al. and partners
University of Idaho, *Kimberly*
– development began in 2000
*– rooted in Dutch **SEBAL** model*

Development Partners

Ricardo Trezza – University of **Idaho**
M. Tasumi – University of Miyazaki, **Japan**
Tony Morse – Spatial Analysis Group, **Boise**
William Kramber – **Idaho** Dept. Water Resources
Wim Bastiaanssen – Water Watch, **Netherlands**
Ayse Kilic – University of **Nebraska**
Jeppe Kjaersgaard – University of **Idaho**

Justin Huntington – Desert Research Inst, **NV**
Jan Hendrickx – **New Mexico** Tech
Ignacio Lorite-Torres – IFAPA, Cordoba, **Spain**
Isabel Pocas – Univ. Lisbon, **Portugal**
Samuel Ortega-Ferias – Univ. Talca, **Chile**
Magali Garcia – Univ. La Paz, **Bolivia**

University of Idaho

METRIC Applications in Idaho

Water Planning

Aquifer Depletion

Hydrologic Modeling

Endangered Species

Agricultural Water Use

Legal Finding-of-Fact

Water Rights Buy-Back

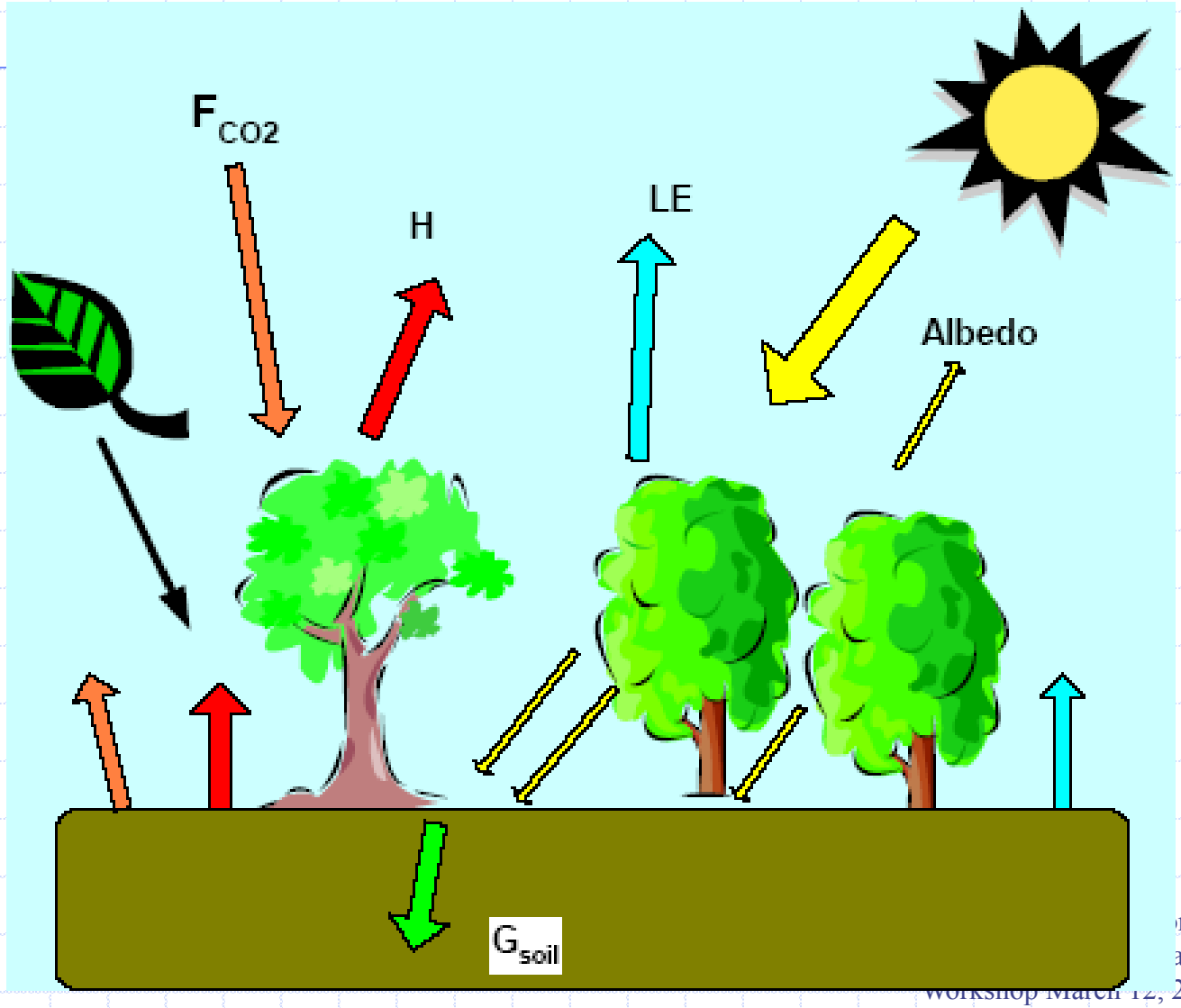
Water Rights Compliance

In-Season Water Demand

Tribal Water Rights Negotiations

Why Energy Balance?

ET is governed by Energy Availability and Aerodynamics

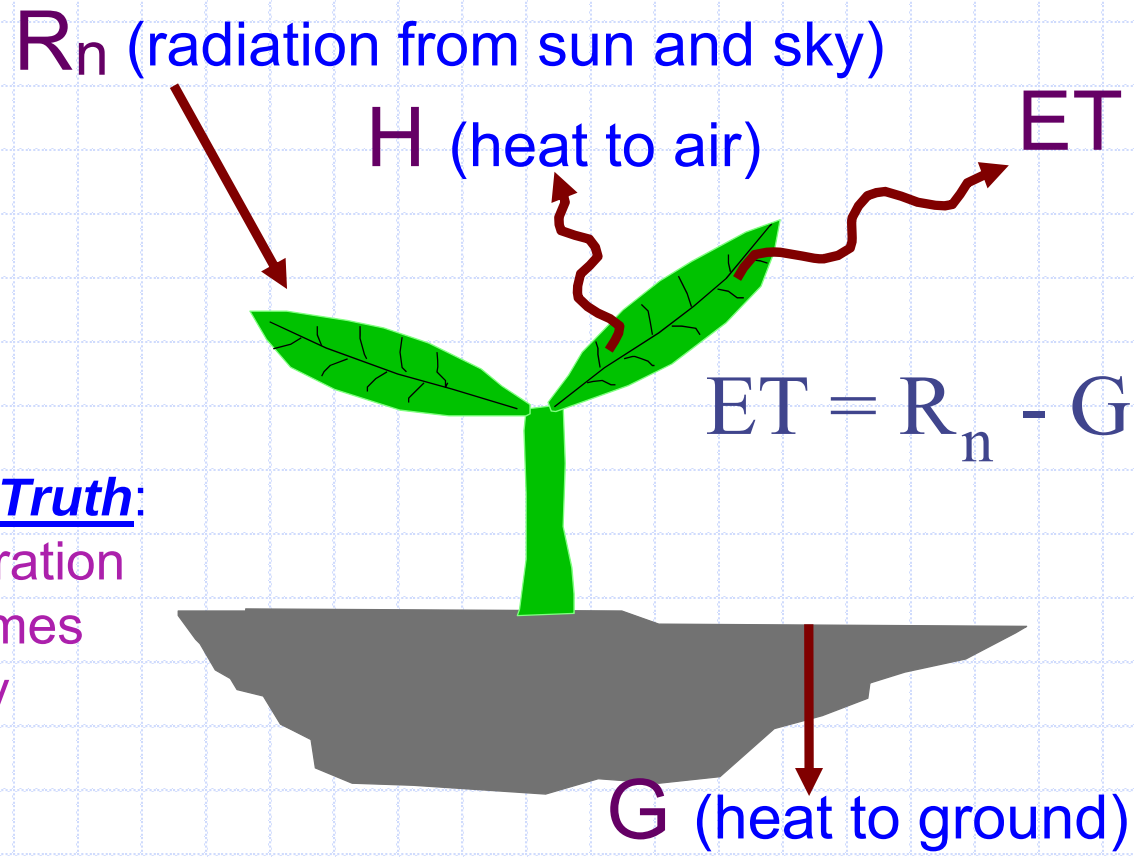


Definitions

- Energy Balance
  - Remember: ET is the part of irrigation water that changes from liquid to water vapor
  - Liquid to vapor conversion requires energy
  - We ‘look’ for the energy used to produce the evaporation
  - This is shown by the temperature of the surface

Why use an "Energy balance"?

- ET is calculated as a "residual" of the energy balance



$$ET = R_n - G - H$$

Basic Truth:
Evaporation consumes Energy

Sensible Heat Flux (H) – METRIC model

$$H = (\rho \times c_p \times dT) / r_{ah}$$

Advantage:
r_{ah} 'floats' above the surface and is 'free' of z_{oh} and some limitations of a single source approach

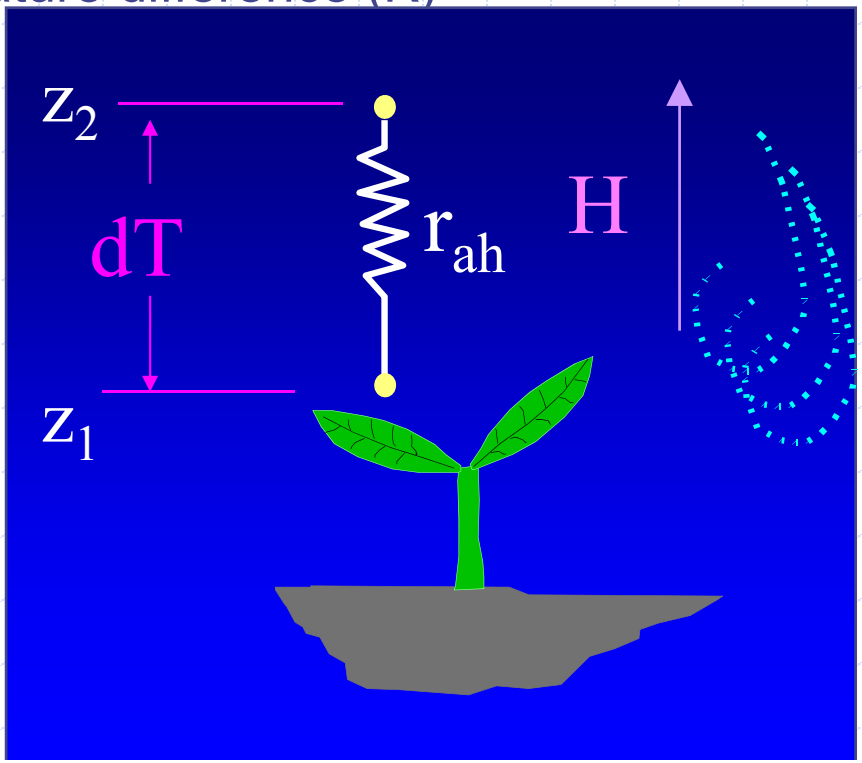
Advantage:
dT is inverse calibrated (simulated) (free of T_{rad} vs. T_{aero} vs. T_{air})

dT = "floating" near surface temperature difference (K)

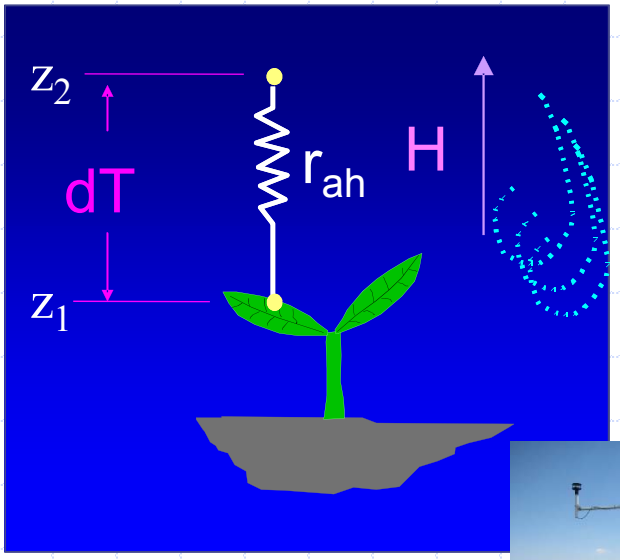
r_{ah} = the aerodynamic resistance from z_1 to z_2

$$r_{ah} = \frac{\ln\left(\frac{z_2}{z_1}\right) - \Psi_{h(z_2)} + \Psi_{h(z_1)}}{u_* \times k}$$

u_* = friction velocity
k = von karmon constant (0.41)



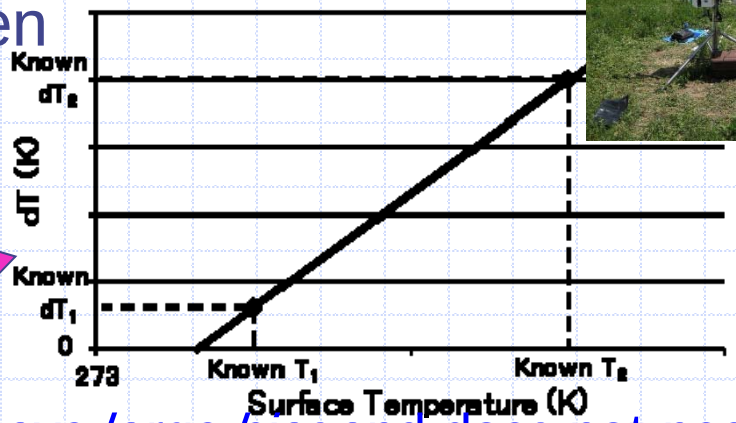
Near Surface Temperature Difference (dT)



- The advantage of the METRIC-CIMEC approach:
  - T_{air} is *unknown* and *unneeded*
  - a linear relationship between T_s and dT is assumed:

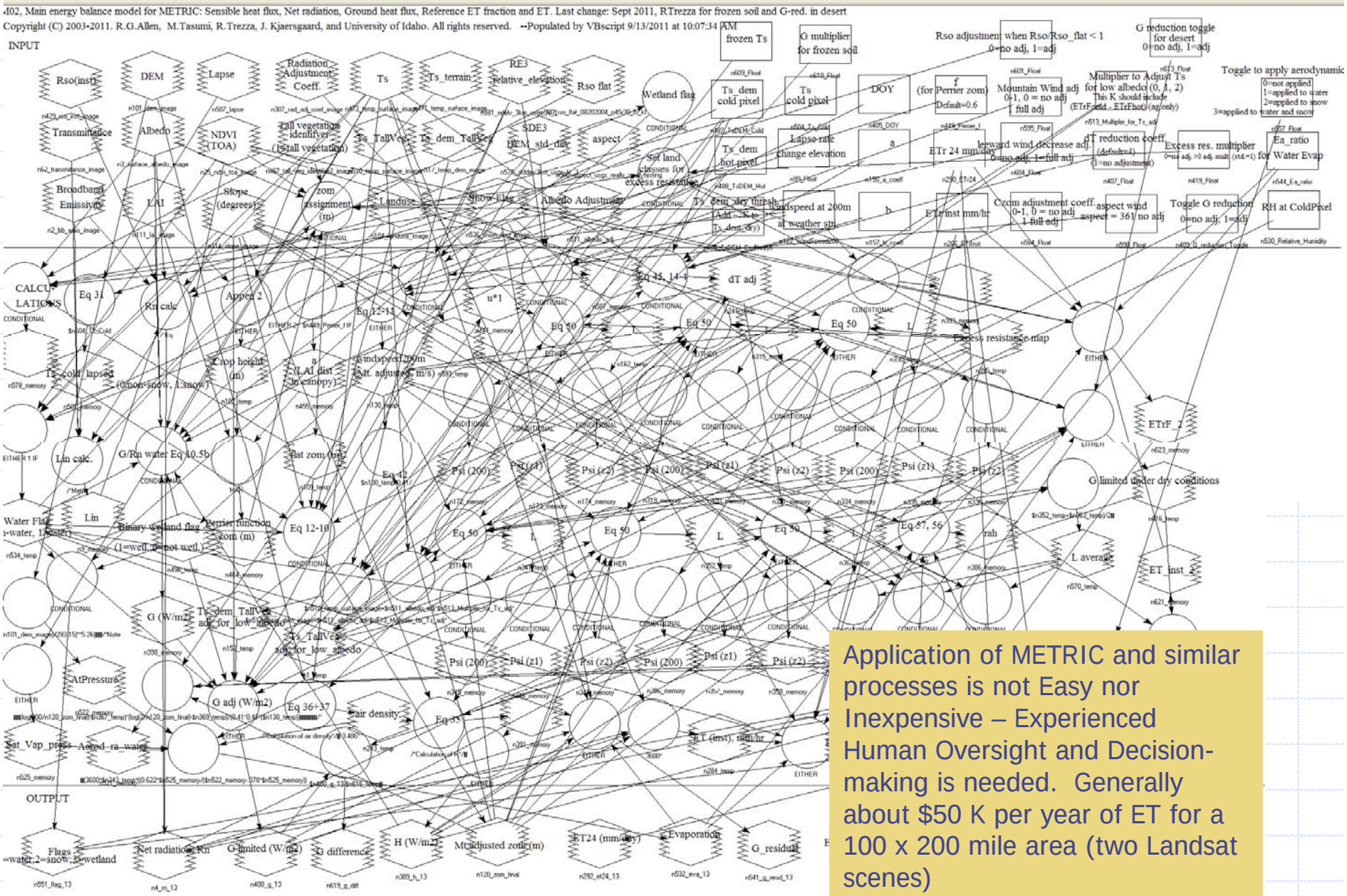
$$dT = b + aT_s$$

Bastiaanssen 'breakthrough'



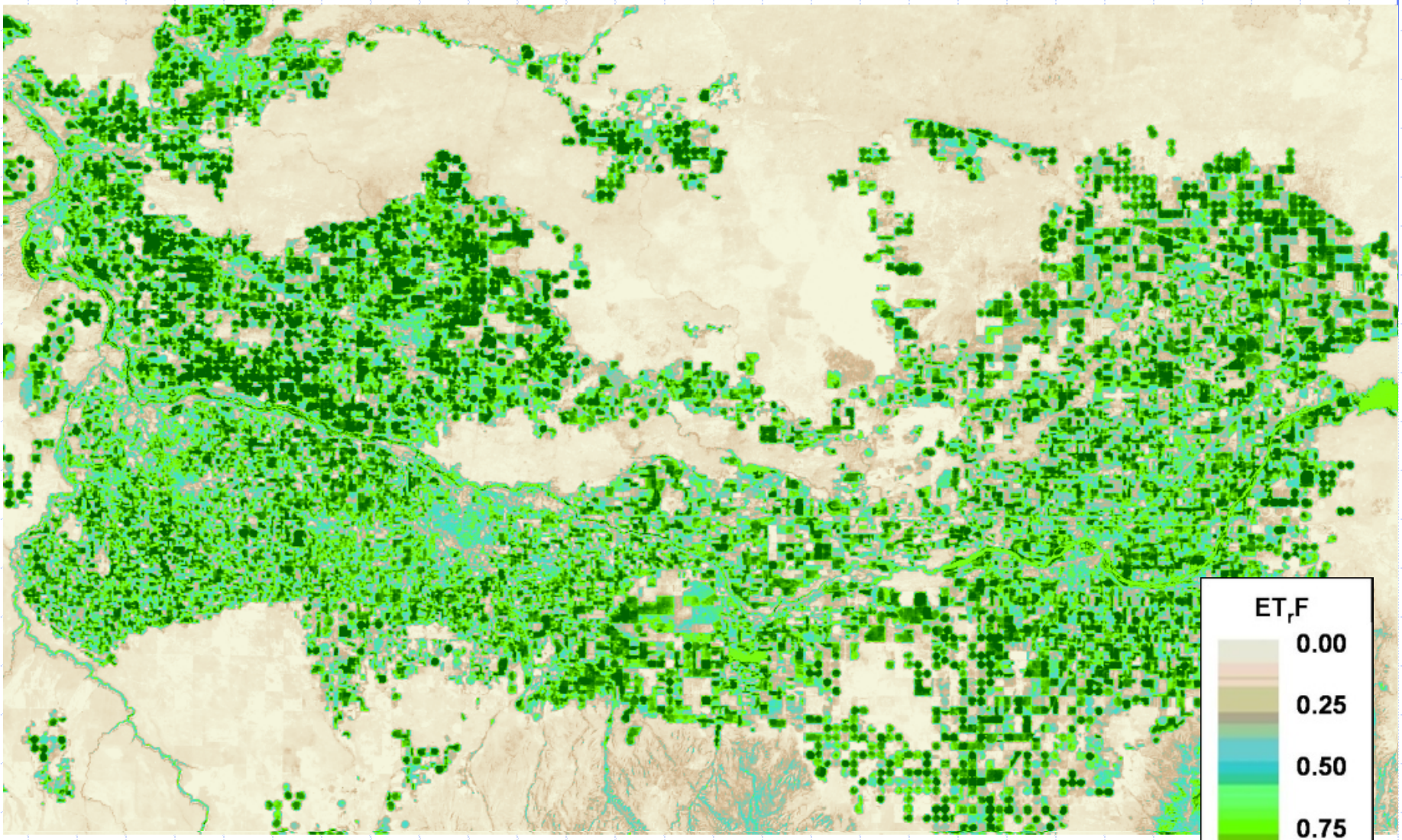
- T_s is *used only as an index* and *can have large bias* and does not need to represent aerodynamic surface temperature

METRIC^{tm}-ERDAS submodel for sensible heat and ETrF



Application of METRIC and similar processes is not Easy nor Inexpensive – Experienced Human Oversight and Decision-making is needed. Generally about $50 K per year of ET for a 100 x 200 mile area (two Landsat scenes)

Time Series of Relative ET near Twin Falls, ID

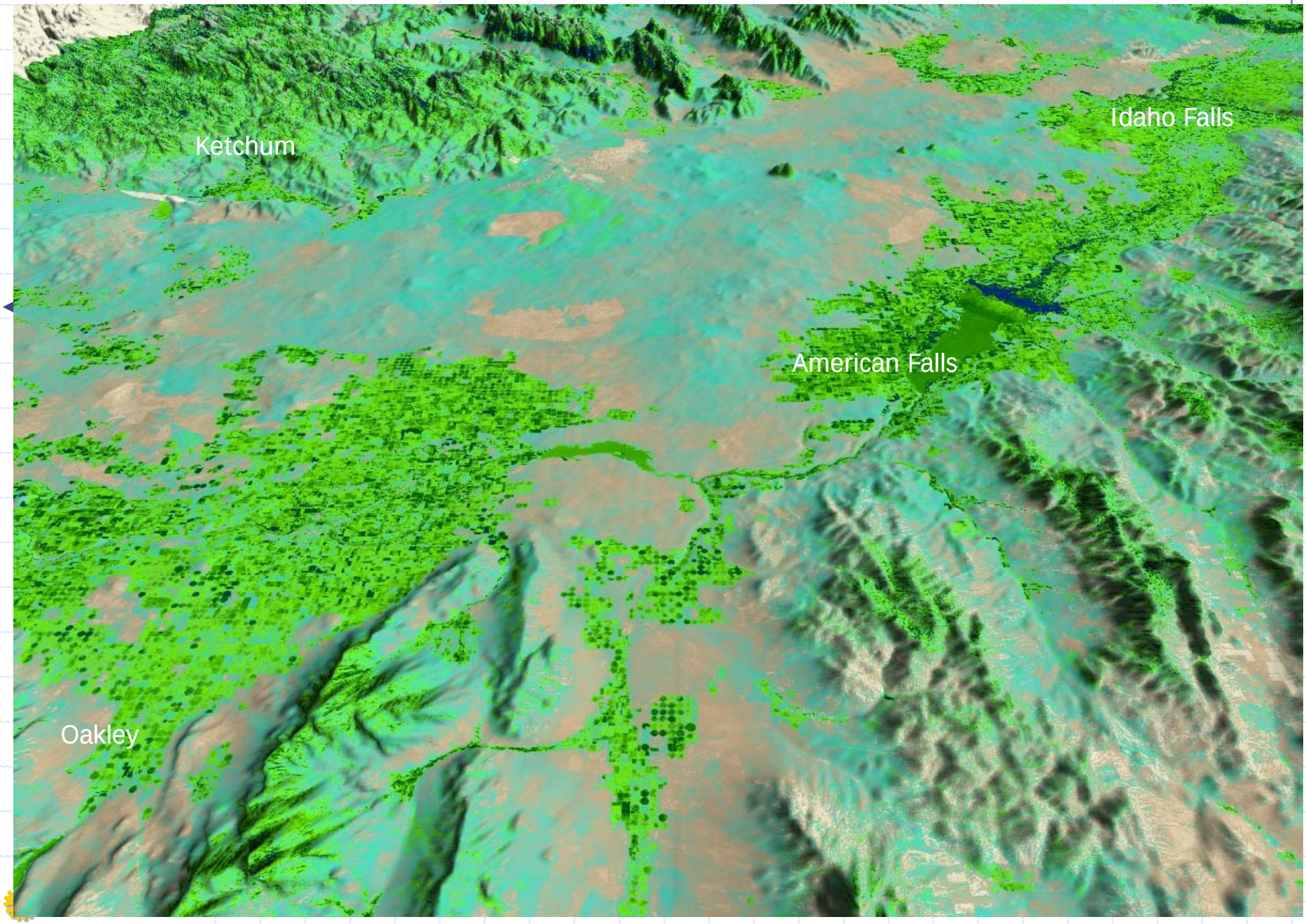


8/22/2000

University of Idaho

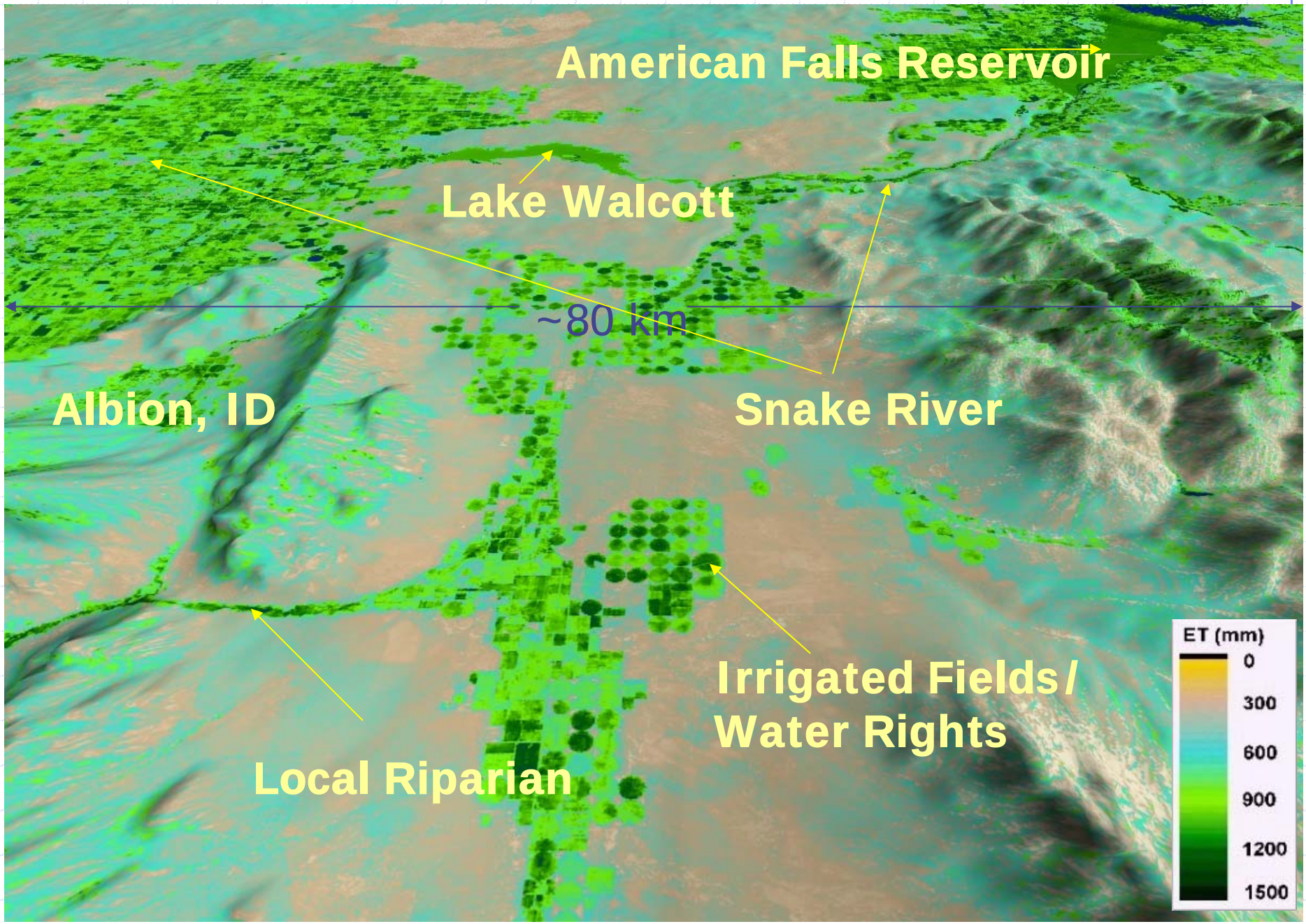
Our Product: Monthly and Seasonal ET at 30 m resolution

April – October, 2006 ET –SE Idaho



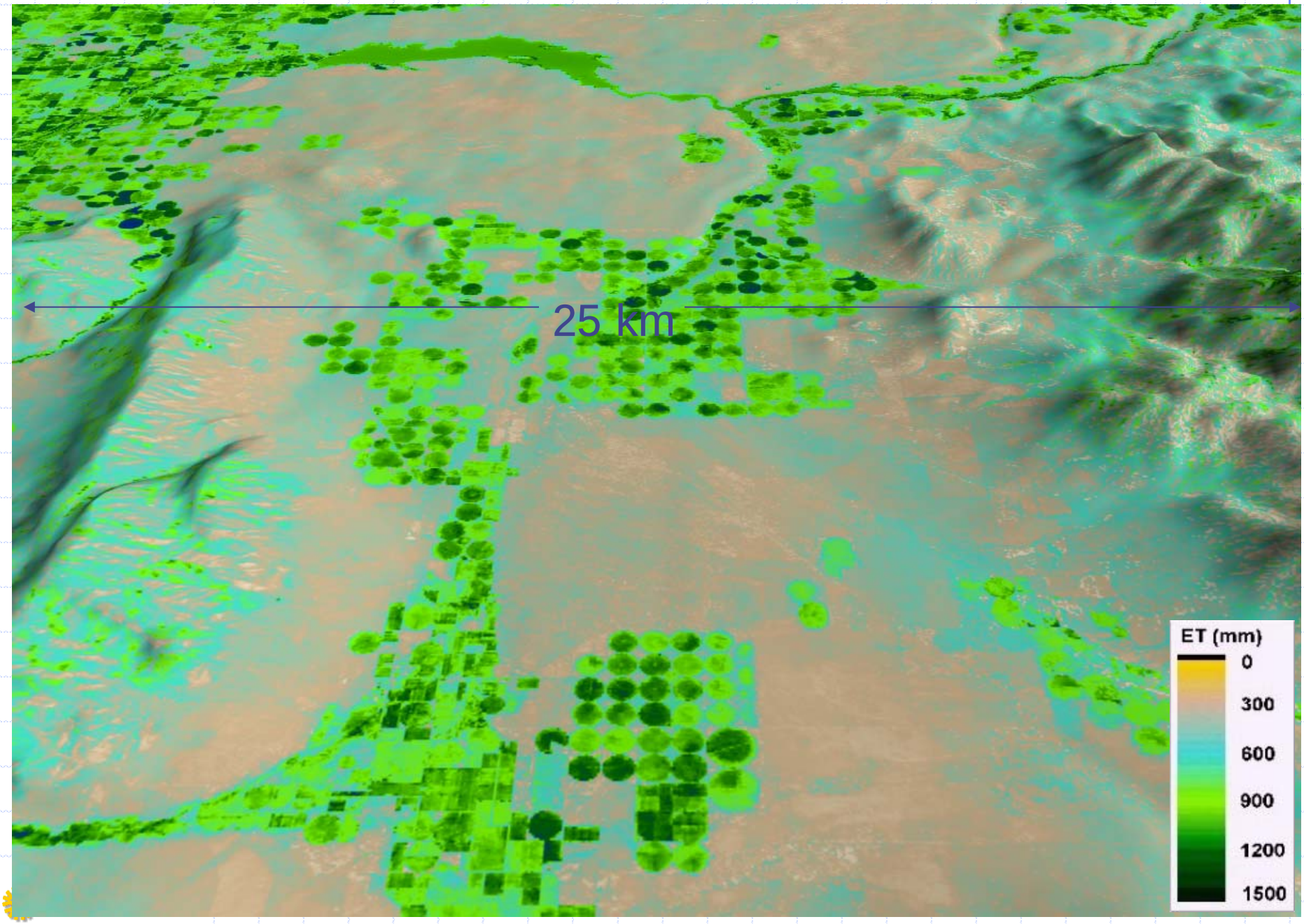
ET features at 30 m resolution

April – October, 2006 ET from METRIC-Landsat



ET features at 30 m resolution

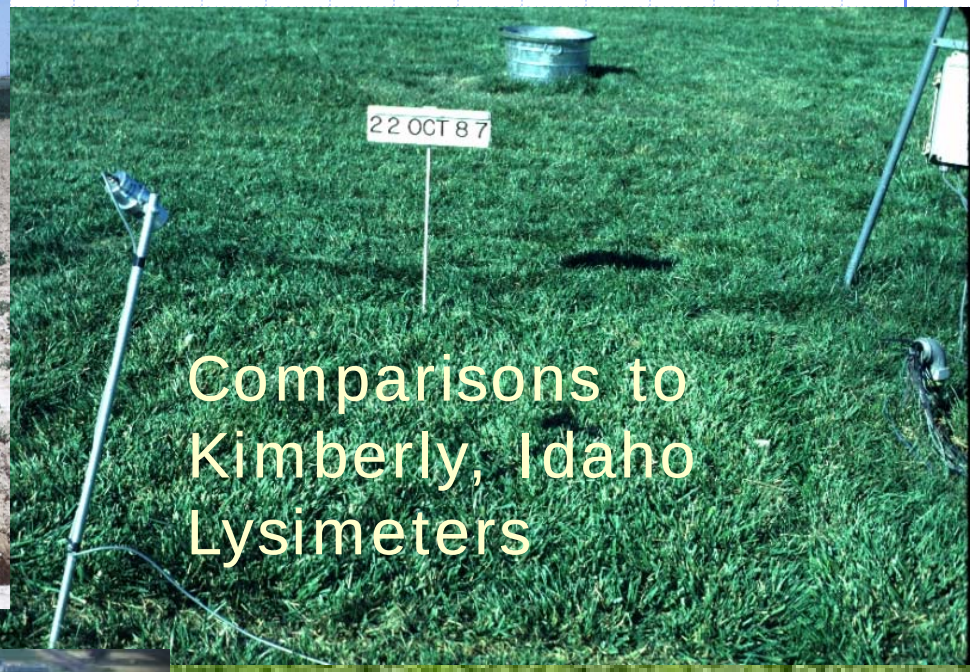
April – October, 2006 ET from METRIC-Landsat



Accuracy

Weighing Lysimeter System at Kimberly, Idaho

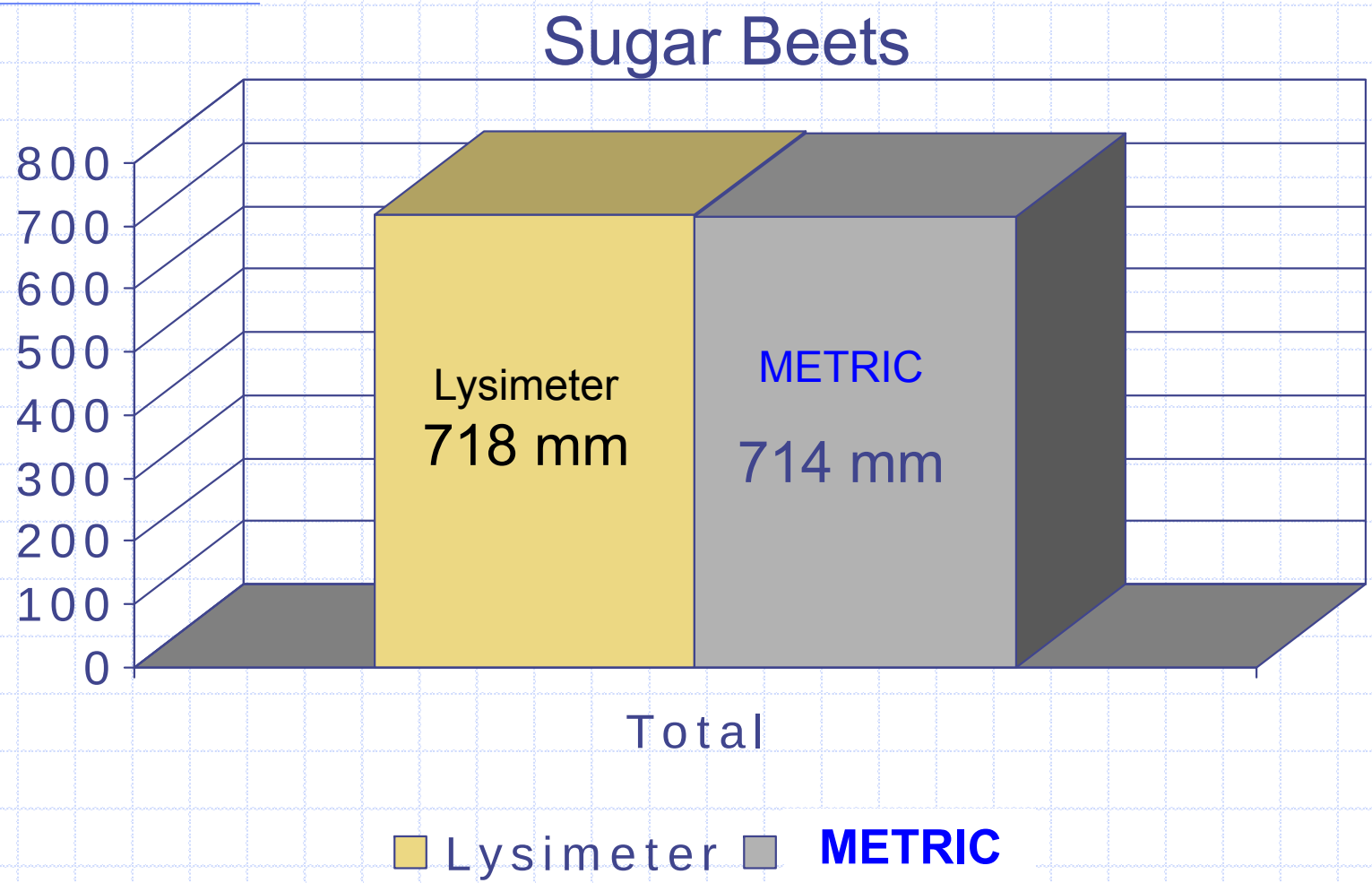
Dr. James L. Wright, USDA-ARS



Comparisons to Kimberly, Idaho Lysimeters

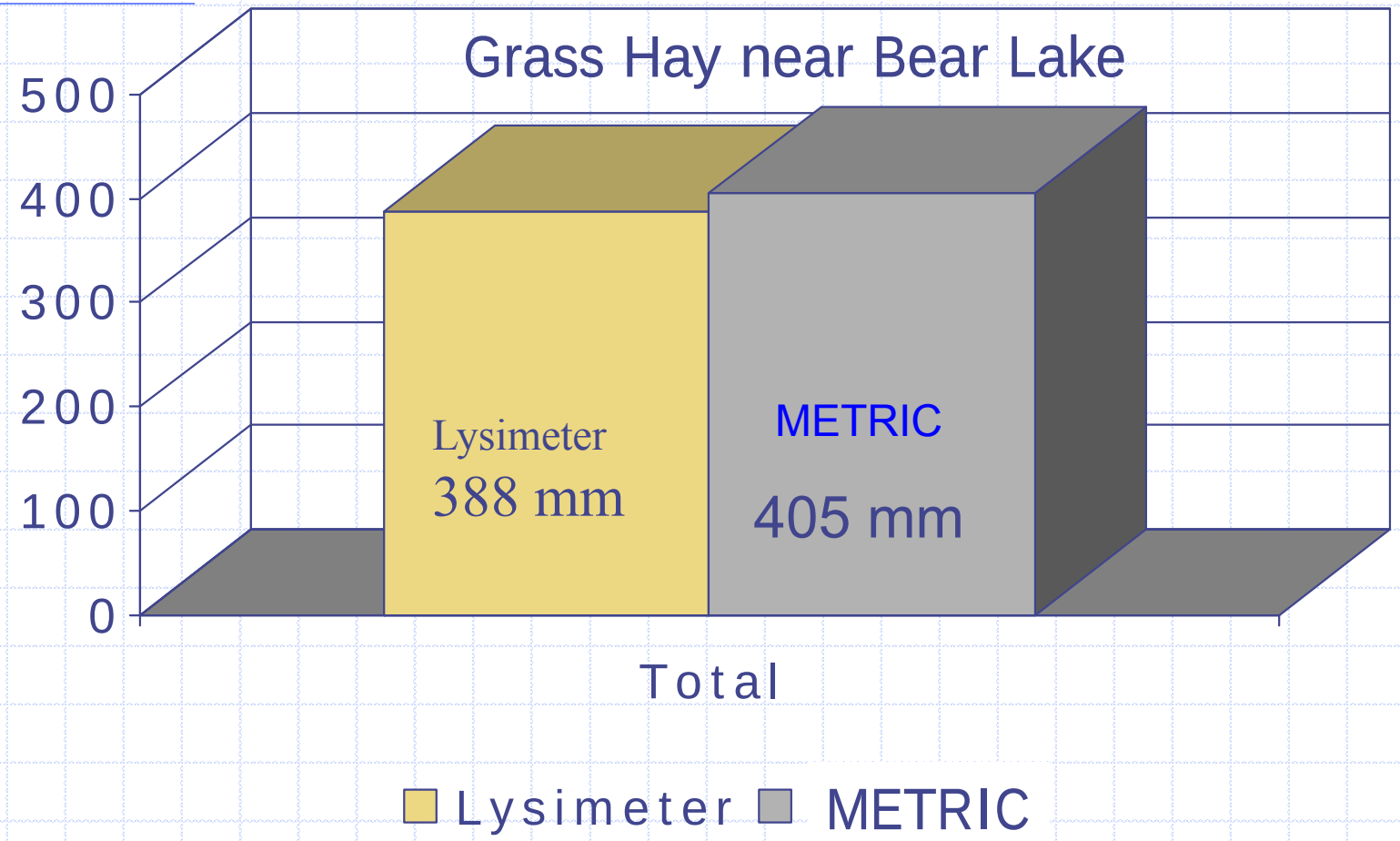
Comparison of Seasonal ET by METRIC^{tm} with Lysimeter

ET (mm) - April-Sept., *Kimberly, 1989*

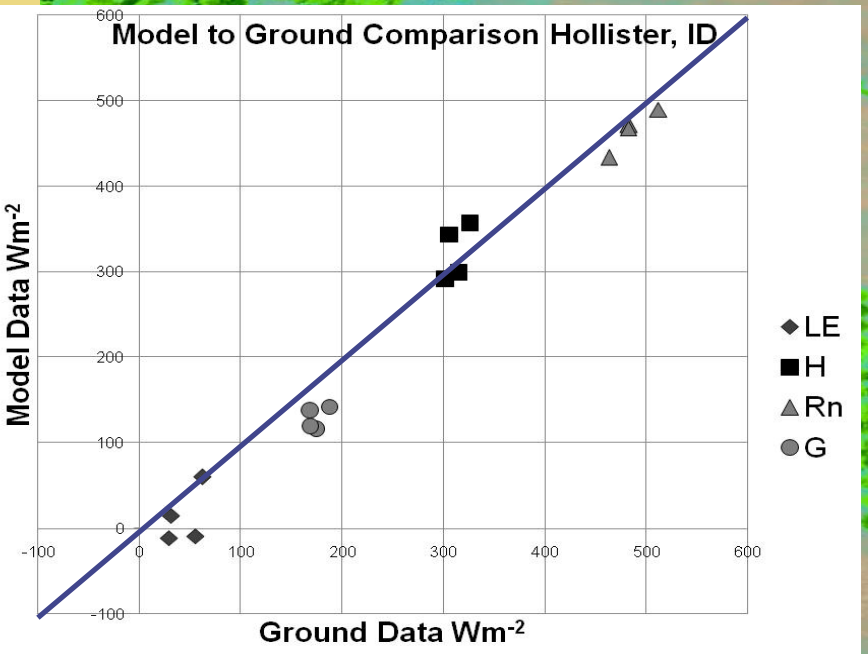


Comparison of Seasonal ET by METRIC$_{2000}$ with Lysimeter

ET (mm) - July-Oct., *Montpelier, ID 1985*



Idaho NSF EPSCoR Flux Sites – Desert Systems

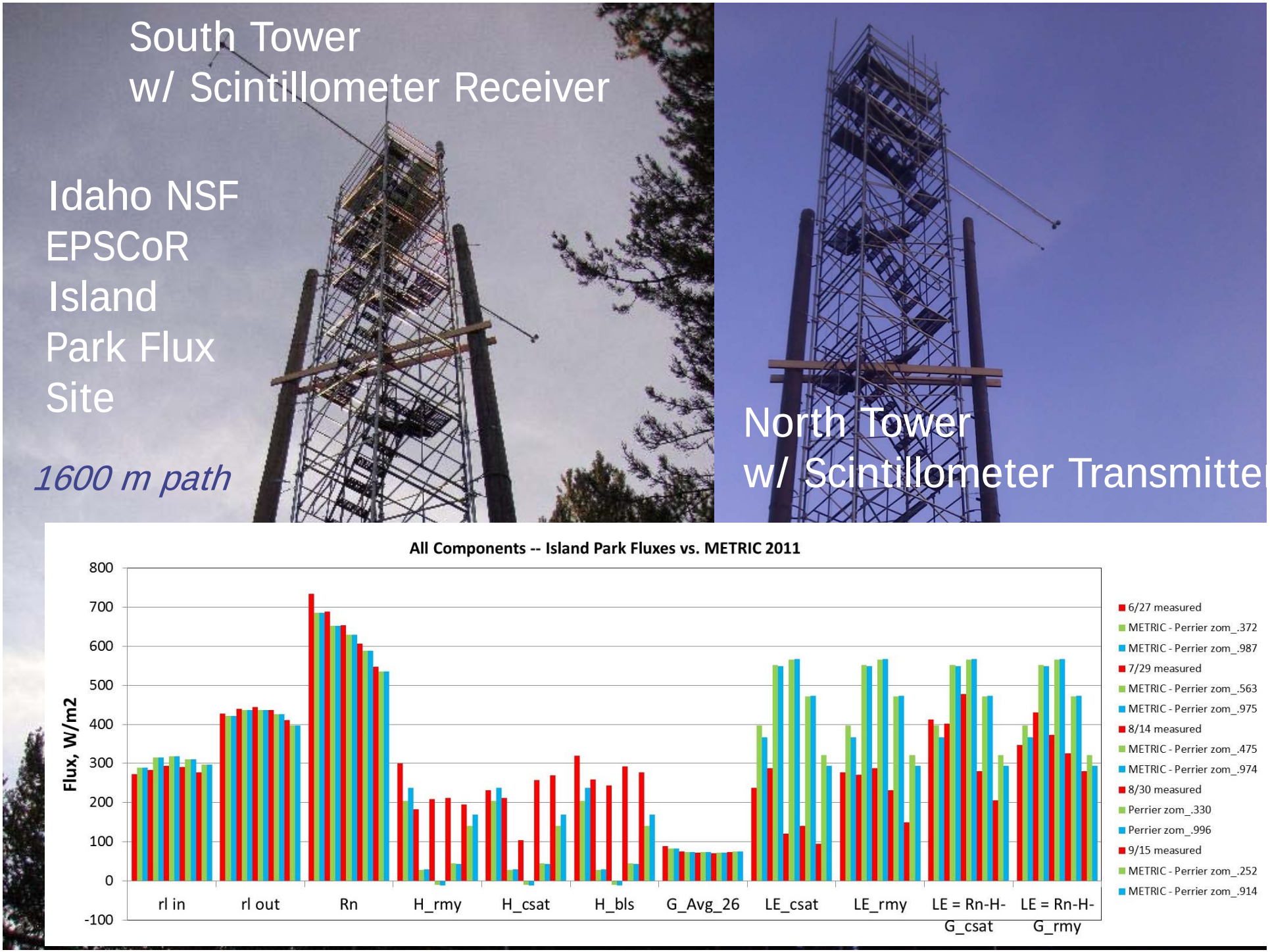


Four Landsat Dates during 2010 – Sagebrush

April – September ET from METRIC

- Comparison of satellite-based surface energy balance (UI METRIC model) with Eddy Covarince to improve modeling for natural systems

Hydroclimate

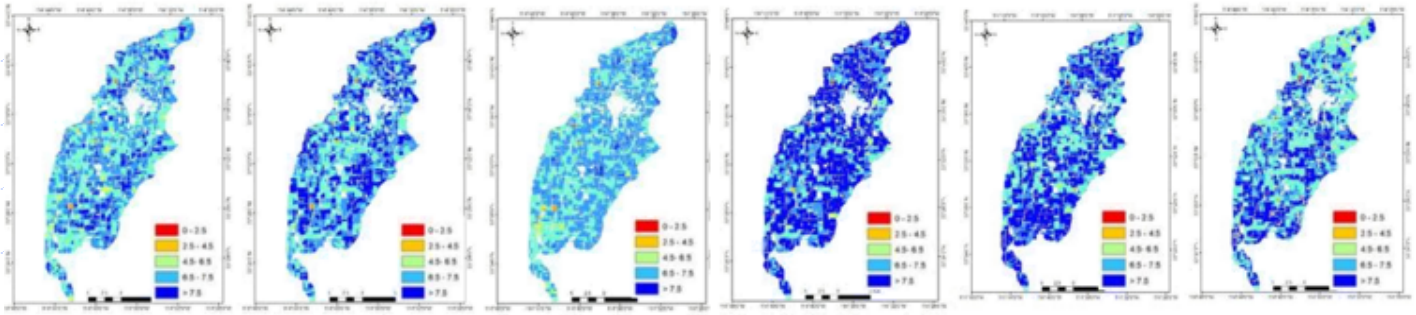

South Tower
w/ Scintillometer Receiver
Idaho NSF
EPSCoR
Island
Park Flux
Site
1600 m path
North Tower
w/ Scintillometer Transmitte
All Components -- Island Park Fluxes vs. METRIC 2011
Flux, W/m2
800
700
600
500
400
300
200
100
0
-100
rl in
rl out
Rn
H_rmy
H_csat
H_bls
G_Avg_26
LE_csat
LE_rmy
LE = Rn-H-G_csat
LE = Rn-H-G_rmy
6/27 measured
METRIC - Perrier zom_.372
METRIC - Perrier zom_.987
7/29 measured
METRIC - Perrier zom_.563
METRIC - Perrier zom_.975
8/14 measured
METRIC - Perrier zom_.475
METRIC - Perrier zom_.974
8/30 measured
Perrier zom_.330
Perrier zom_.996
9/15 measured
METRIC - Perrier zom_.252
METRIC - Perrier zom_.914

“Blind” Intercomparison of Leading ET models – 2014 – SE California

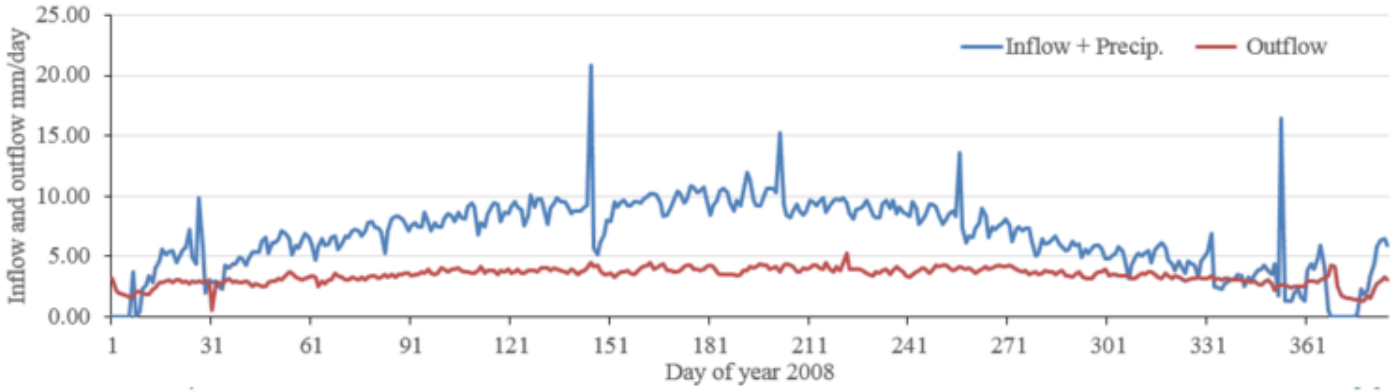
Requested/Expected Results from Modelers

1. Estimates of surface energy balance fluxes (if any) and daily actual ET during satellite overpass dates in terms of individual images. Including discerption of extrapolation method from instantaneous to daily values of ET.
2. Estimates of total daily actual ET for the entire area for the entire year of 2008. only tabulated value is needed.

May 10 | May 17 | May 26 | June18 | July13 | July 29



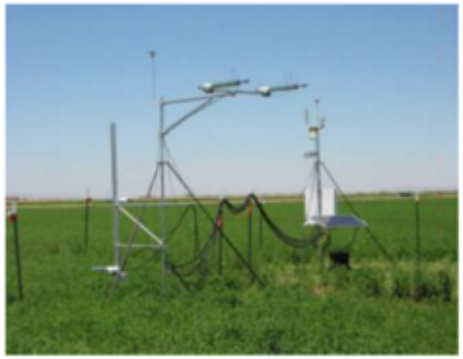
Comparison of actual daily ET (mm/day) during summer of 2008 based on TSEB model



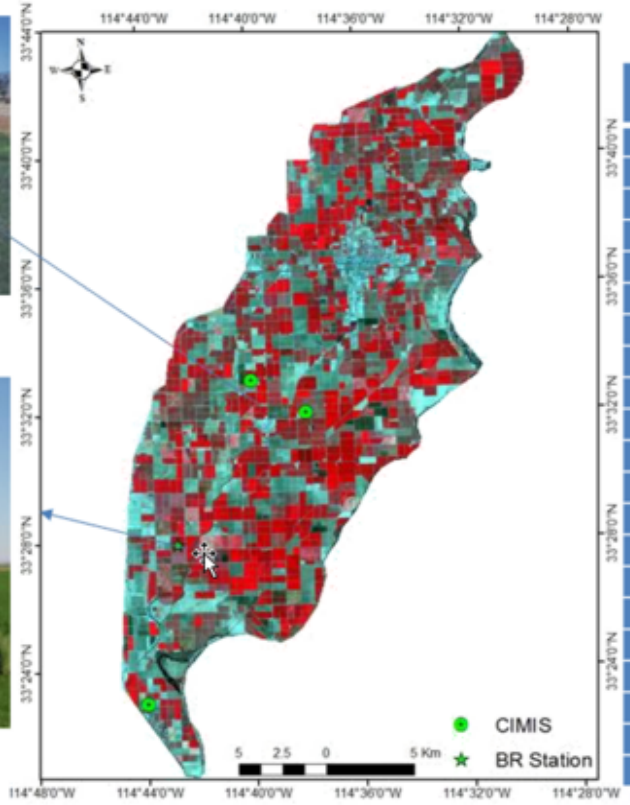
“Blind” Intercomparison of Leading ET models – 2014 – SE California

Site 1: Palo Verde Irrigation District (PVID)

CIMIS Weather Station , Blythe NE # 135



Full surface energy balance flux measurements based on Bowen Ratio Station



False color RGB , NIR-Red-Green Landsat 5 image during DOY 131, May 10, 2008

List of Landsat 5 scenes used

No.	Date (2008)	DOY (2008)	Path	Raw
1	19-Jan	19	38	37
2	11-Feb	42	39	37
3	27-Feb	58	39	37
4	07-Mar	67	38	37
5	23-Mar	83	38	37
6	08-Apr	99	38	37
7	24-Apr	115	38	37
8	10-May	131	38	37
9	17-May	138	39	37
10	26-May	147	38	37
11	11-Jun	163	38	37
12	18-Jun	170	39	37
13	13-Jul	195	38	37
14	29-Jul	211	38	37
15	05-Aug	218	39	37
16	21-Aug	234	39	37
17	15-Sep	259	38	37
18	01-Oct	275	38	37
19	17-Oct	291	38	37
20	09-Nov	314	39	37
21	18-Nov	323	38	37

UtahState University

USGS science for a changing world

University of Idaho

"Blind" Intercomparison of Leading ET model

Summ

Individual – vs. Grou

	RMSE	BIAS
Measured		
SSEBop	1.5	-0.2
SEBS	2.7	-2.5
METRIC	0.9	-0.1
ReSET	1.3	-0.8
PT-JPL		
DisALEXI	2.1	-1.7

Seasonal Water Balance

Water balance Component	Depth (mm/year)	DisALEXI	ReSET	METRIC	SSEBop	SEBS	P-T
Precipitation	71	71	71	71	71	71	71
Inflow Main Canal	2479	2479	2479	2479	2479	2479	2479
Total Inflow	2550	2550	2550	2550	2550	2550	2550
Canal Spills	284	284	284	284	284	284	284
Drainage	998	998	998	998	998	998	998
ET	**(1000)**		**956**	**1223**	**952**	**X**	
Total Outflow	(2282)		2238	2505	2234	X	
Inflow- Outflow	(268)		312 (-12.2%)	34 (-1.8%)	316 (-12.4%)	X	

Accuracy of METRIC was < % for both individual field and entire district

University of Idaho

ET Investigations involving METRIC/Landsat -- Applications for Water Management

University of Idaho and Associates/Partners

Richard Allen (UI), Ricardo Trezza (UI), Bill Kramber (IDWR), Tony Morse (SAG), Jan Hendrickx (NMT), Ayse Irmak (UNL), Justin Huntington (DRI), Clarence Robison (UI), Carlos Kelly (UI), Jeppe Kjaersgaard (UI), Jeremy Greth (UI), Masahiro Tasumi (UI), Tim Martin (RTI)

UI: University of Idaho
IDWR: Idaho Department of Water Resources
SAG: Spatial Analysis Group (Morse)
NMT: New Mexico Tech
UNL: University of Nebraska, Lincoln
DRI: Desert Research Institute

RTI: Riverside Technologies, Inc, Fort Collins CO
SHA: Soil Hydrology Associates, Los Lunas NM (Hendrickx)
MDNRC: Montana Department of Natural Resources and Cons
OSE: Office of State Engineer
NRD: Natural Resource District

ET+: Evapotranspiration Plus, Twin Falls ID (Allen)
MBMG: Montana Bureau of Mining and Geology
SNA: SEBAL North America
NMSU: New Mexico State University
CSU: Colorado State University

Flathead Valley, MT

Yakima River Basin -- calibration of large scale energy balance models for assessing climate change. (Univ. Wash.)

Flathead Indian Reservation -- irrigation water consumption for managing streamflows (UI for MDNRC)

Klamath Basin -- water for grazing and local ecosystem interactions, ground water balance, irrigated areas (UI, ET+ for USGS, USFS)

Ground water recharge estimation in four basins: Helena, White Sulpher Springs, Dillon, and Bozeman. (UI for USGS, MBMG)

Lemhi River -- irrigation management for salmon recovery (IDWR, UI for IDWR)

Green River/Upper Colorado River (UWYO, SHA, RTI, ET+ for WY-OSE)

Upper North Platte -- water decree compliance (RTI, ET+)

Ogallala aquifer -- ground water management, mitigation and Riparian ET (UNL, UI for NRDs)

Central Iowa -- ET from Agriculture (USDA-ARS, UI)

Boise River Valley -- agricultural to urban land use change (IDWR for IDWR)

Richard Allen
University of Idaho

Justin Huntington
DRI

Eastern Snake Plain -- irrigation transfers, ground water model calibration (UI for IDWR)

Tim Martin
RTI

Ayse Irmak
UNL

Martha Anderson
USDA-ARS

Bear River -- Interstate Compact (UI for IDWR)

Central Nebraska -- comparison

Owens Valley -- ET of Desert (NMSU)

Western Nevada -- water transfers between irrigated agriculture, municipalities, and playas. (DRI, UI, NV-OSE for NV-OSE)

Middle Rio Grande -- water consumption by invasive vegetation (UI for USDOJ)

Jan Hendrickx
NMT

Lower Rio Grande -- water use by irrigated agriculture (NMSU, UI, for NM-OSE)

Palo Verde Irrigation District - intercomparison of ET methods (USU, USGS, USBR, UI)

Amarillo Area (USDA-ARS, UI)

Lubbock Region (SHA)

Tampa Bay Water (ET+ for TBW)

Tampa Bay Area, FL

Imperial Irrigation District, CA

Walker River, NV

Middle Rio Grande, NM

Eastern Snake Plain, ID

Landsat

MODIS

Minidoka, ID

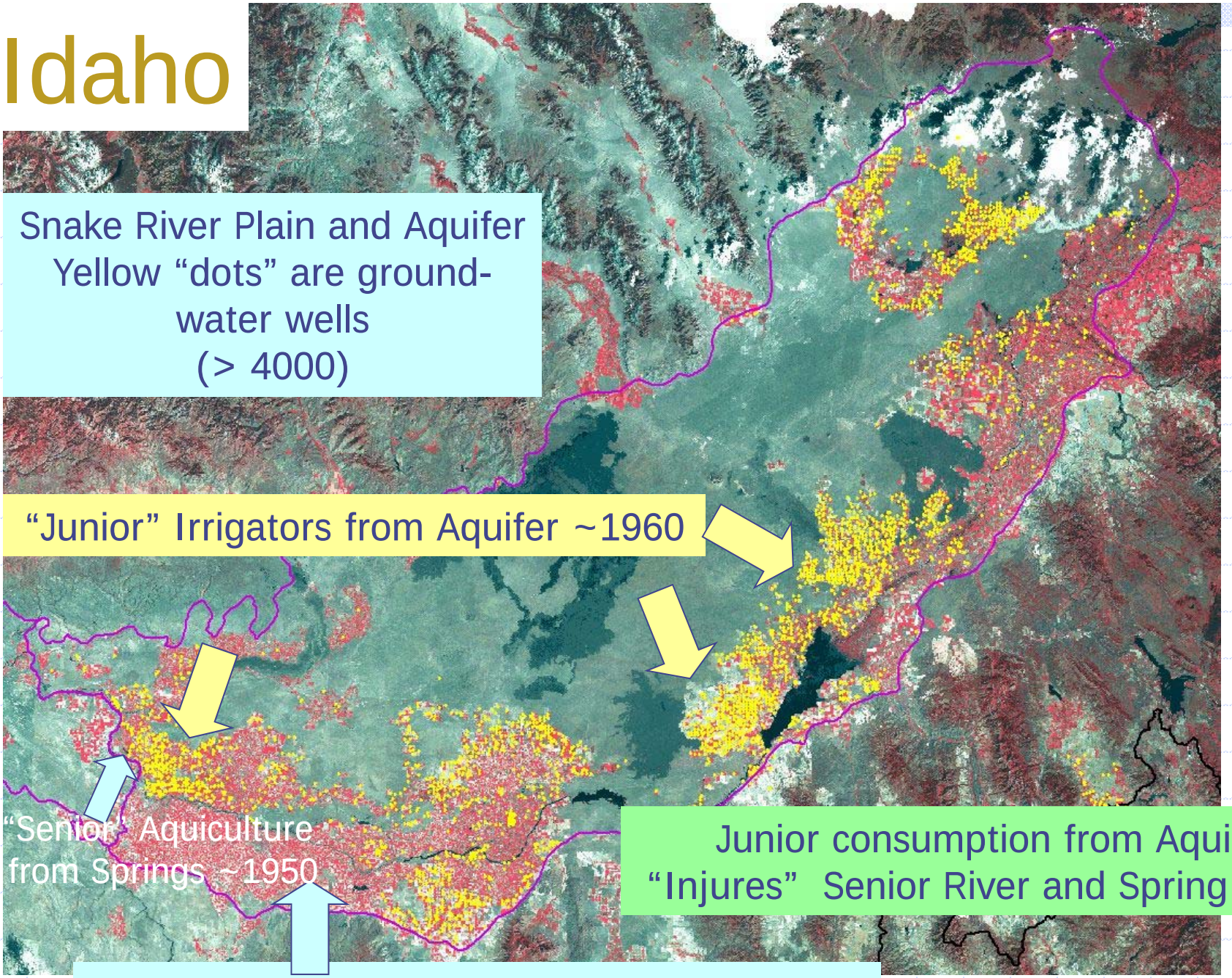
Upper North Platte River, WY

Southern Idaho Fields

Applications

University of Idaho
A LEGACY OF LEADING

Idaho


Snake River Plain and Aquifer
Yellow "dots" are ground-water wells
(> 4000)
"Junior" Irrigators from Aquifer ~1960
"Senior" Aquiculture from Springs ~1950
Junior consumption from Aquifer
"Injures" Senior River and Spring Rights
"Senior" Irrigators from River ~1900

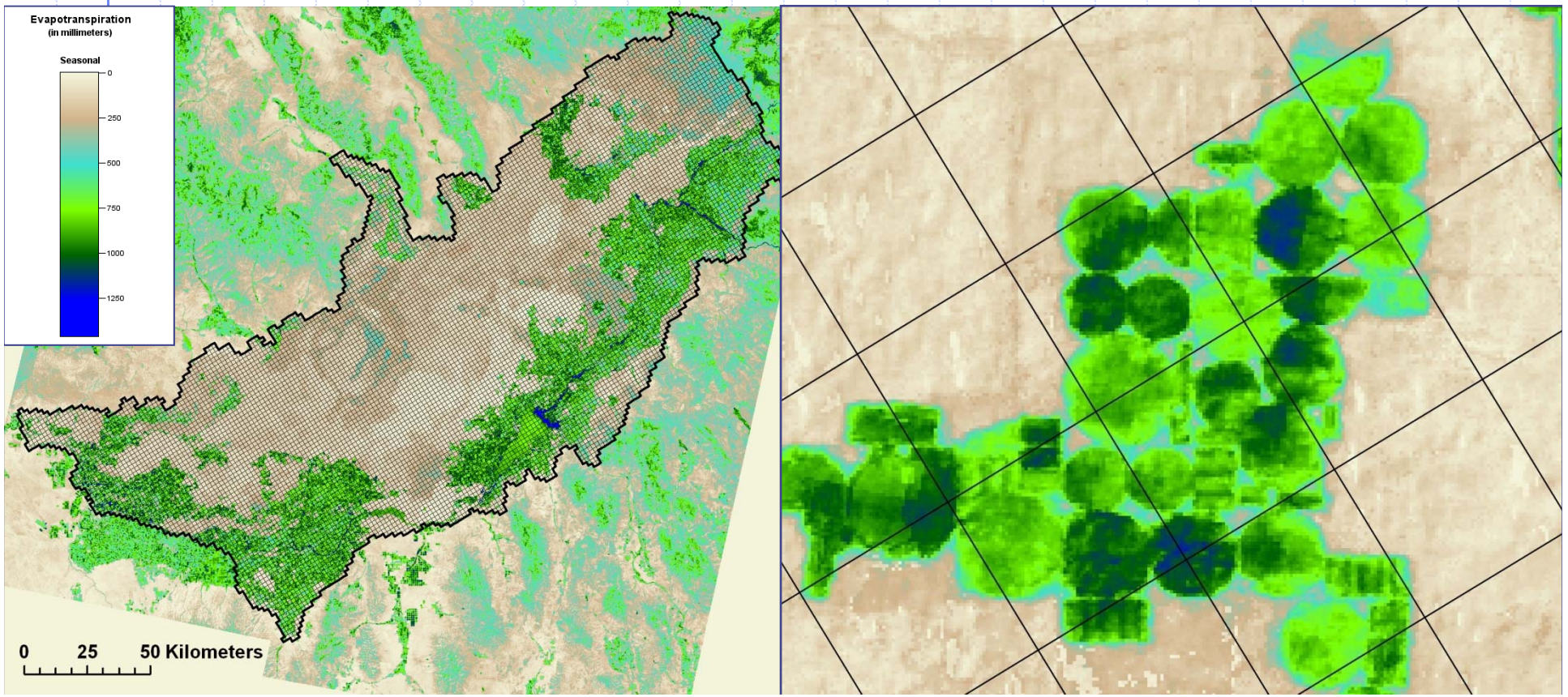
Idaho

Hydrologic Modeling

Eastern Snake Plain Aquifer Model

Developing METRIC ET data from 1986 to present.

ET is used to calculate a water balance for each model grid cell.

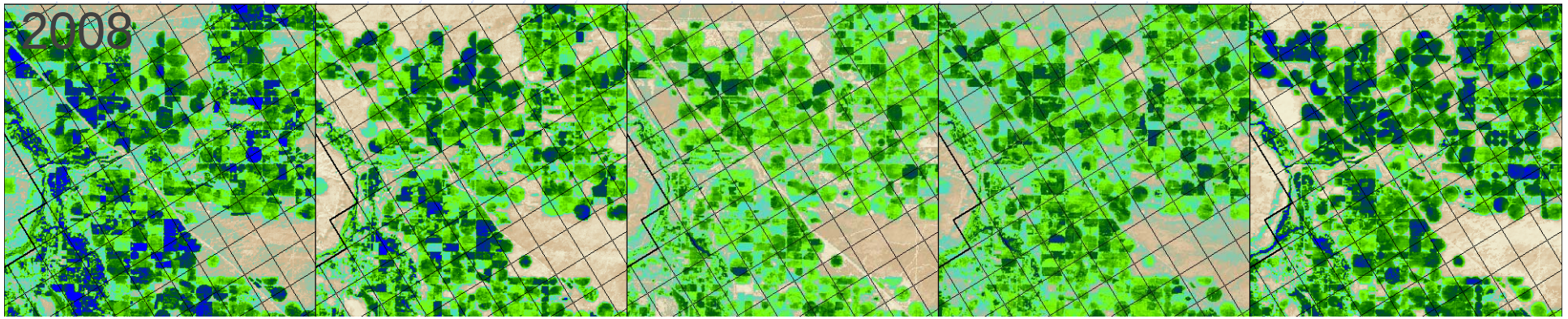


Idaho

Eastern Snake Plain Aquifer Model

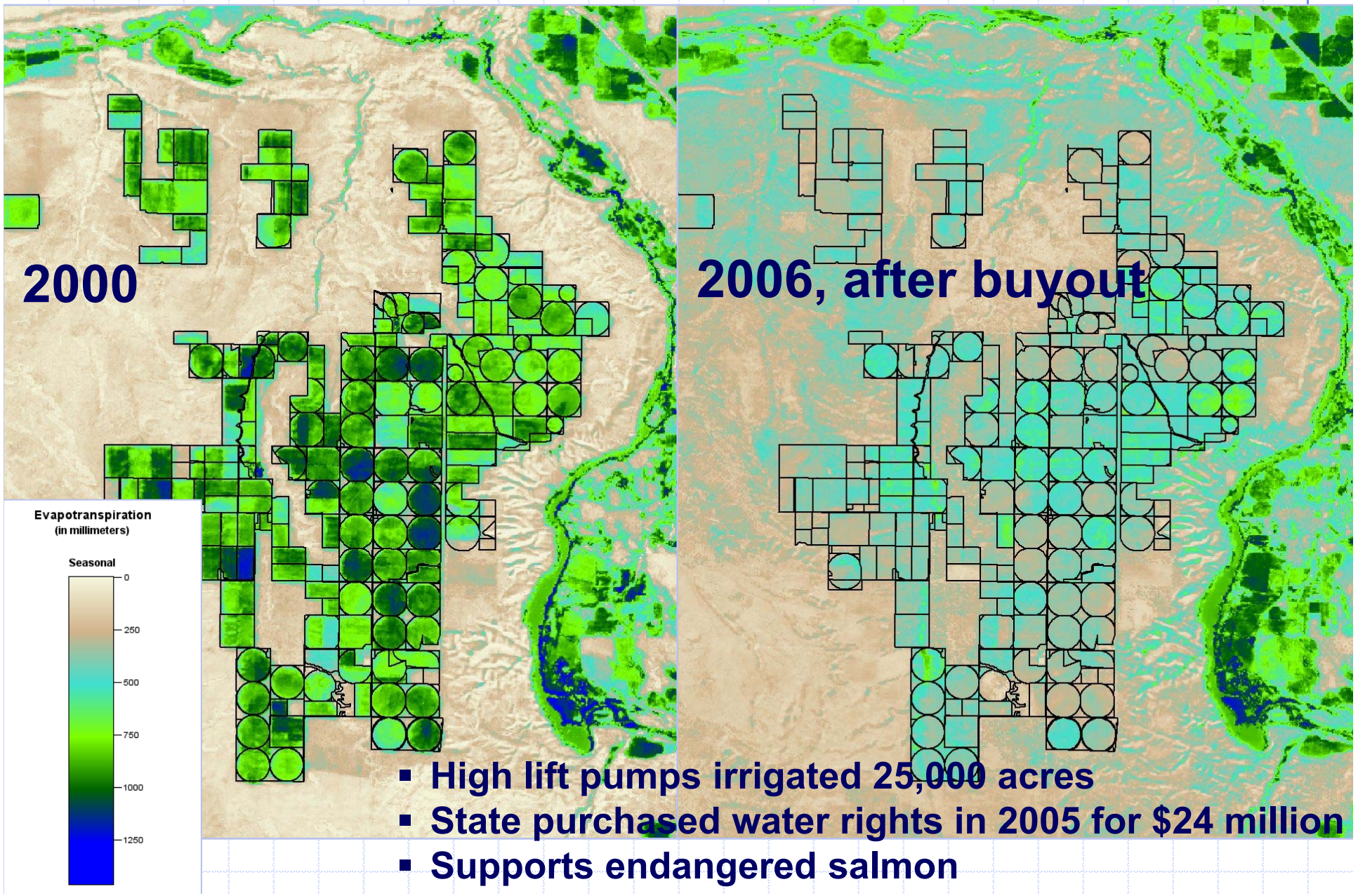
METRIC ET data:

- More accurately calibrate the groundwater model
- Improve accuracy of depletions and recharge estimates
- Shows long term trends and annual variation in ET



Idaho

Bell Rapids Irrigation Project, Idaho: Seasonal ET



- High lift pumps irrigated 25,000 acres
- State purchased water rights in 2005 for $24 million
- Supports endangered salmon

Idaho Clear Springs Foods Water Call

Idaho Business *News*

Water curtailment ordered in Magic Valley

POSTED: 11:13 MDT Thursday, July 23, 2009
by IBR Staff

Idaho Department of Water Resources Interim Director Gary Spackman on July 22 issued a **curtailment order** to about 250 holders of 315 junior water rights in south central Idaho's Magic Valley. The curtailment order is part of a continuing response to a water delivery call made in 2005 by senior water right holder Clear Springs Foods.

State goes ahead with first large-scale well closure of more than 300 water rights in M.V.

7/31/2009

Water districts have limited options, could file a stay

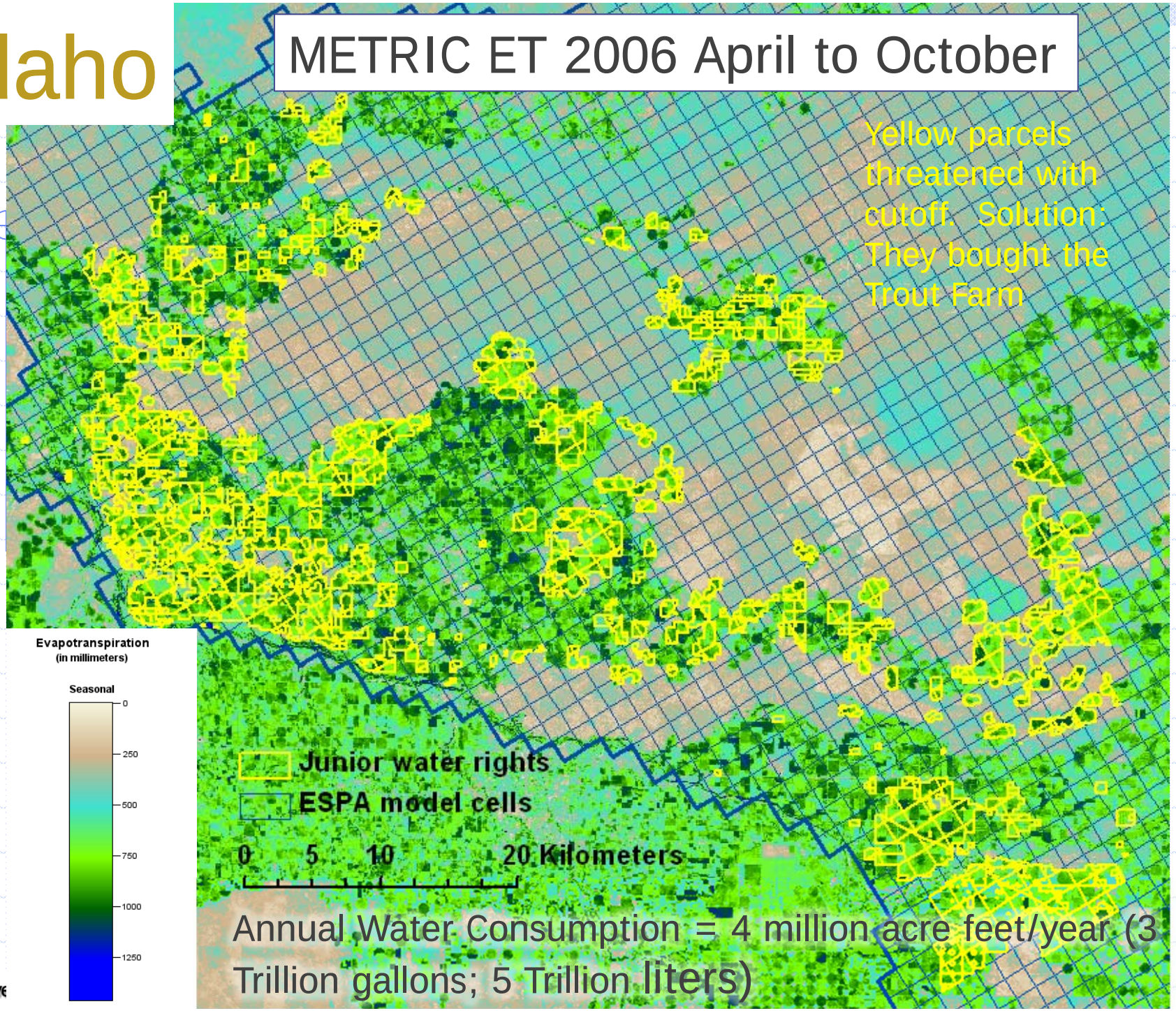
By Nate Poppino
Times-News writer

The Idaho Department of Water Resources will go forward this morning with a plan to shut off more than 300 water rights irrigating just less than 9,000 acres of Magic Valley farmland, the first wide-scale well curtailment to actually be carried out by the state.


Idaho
Clear Springs Foods, Inc.

Idaho

METRIC ET 2006 April to October

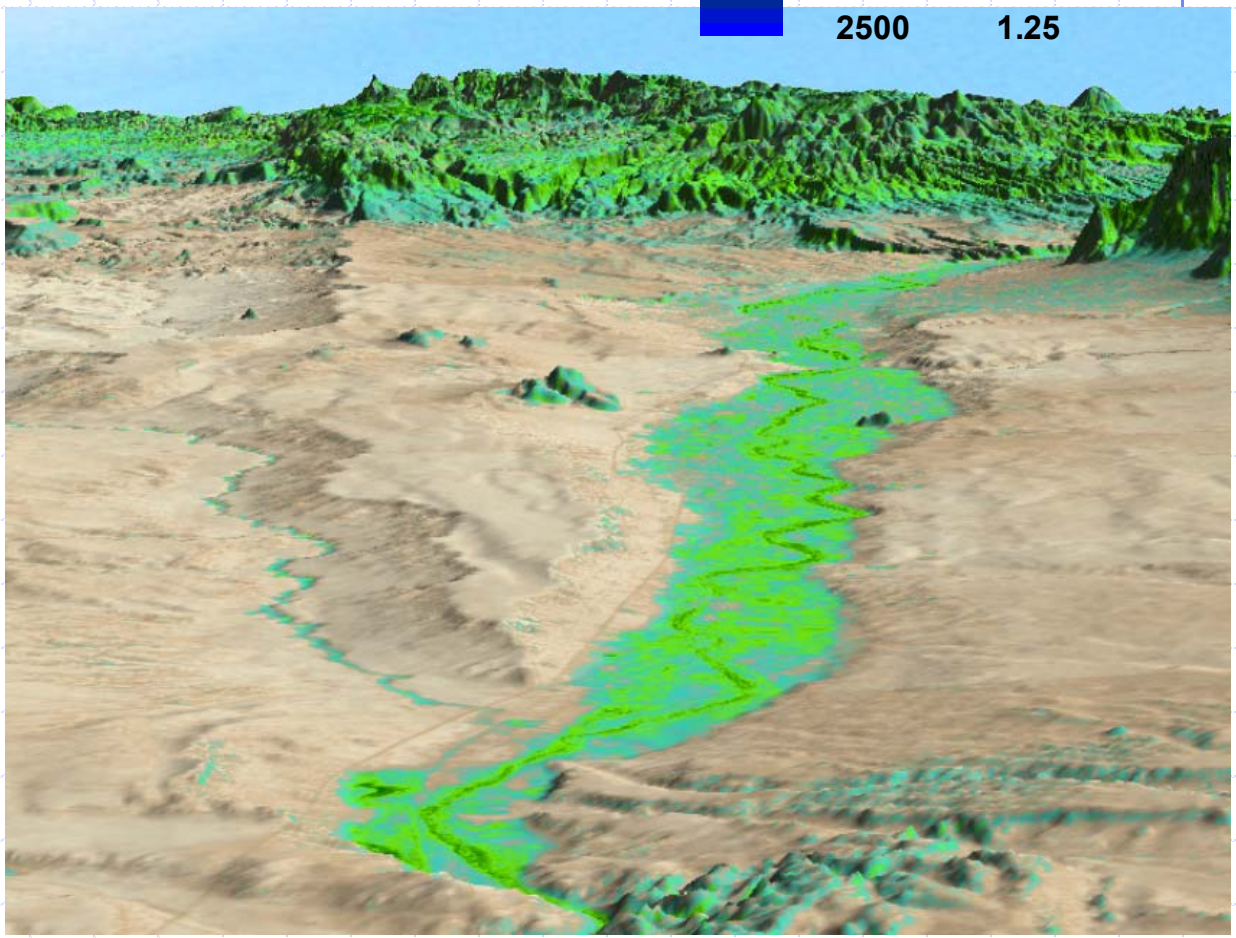


Annual Water Consumption = 4 million acre feet/year (3 Trillion gallons; 5 Trillion liters)

New Mexico

Rio Grande of New Mexico

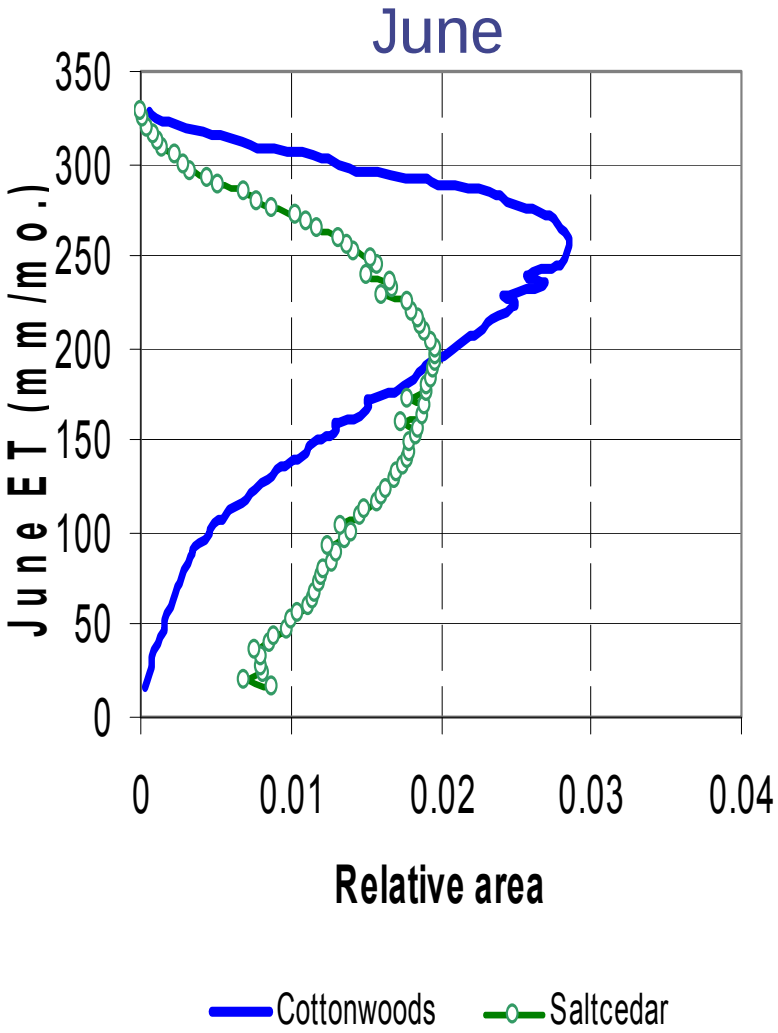
- Pueblo *(native American)* water rights dating to Coronado in 1500's
- Invasion of salt cedar
- Does increased pecan production increase ET from irrigated agriculture?

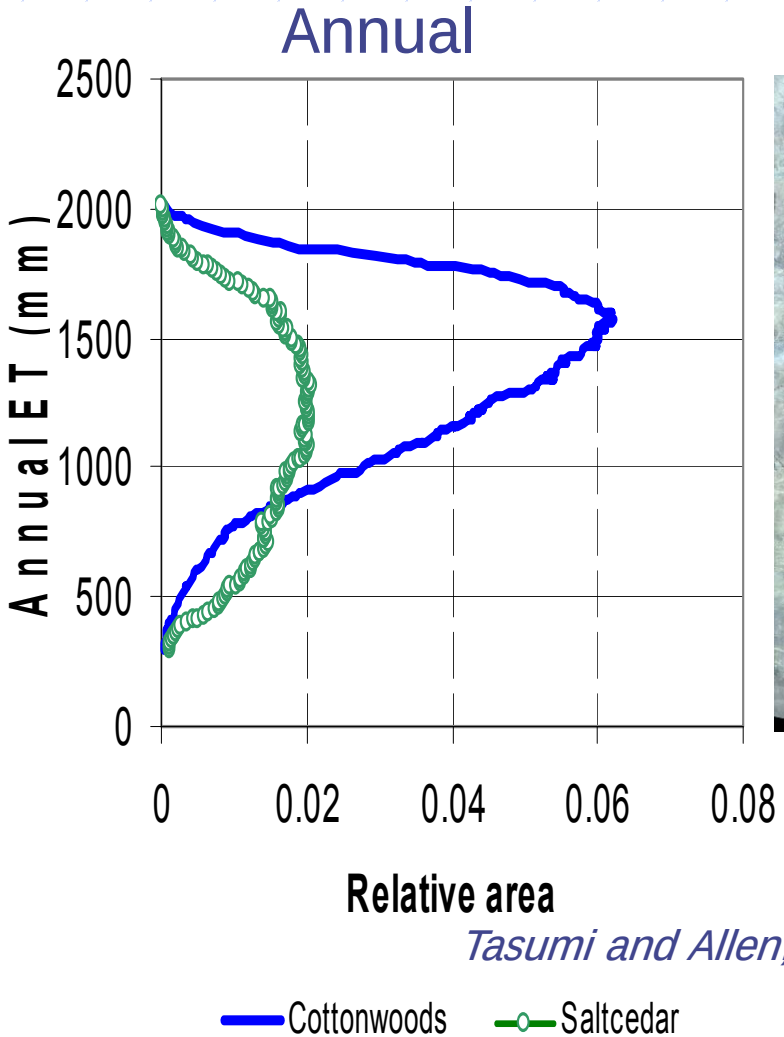


New Mexico

Frequency Distribution of ET

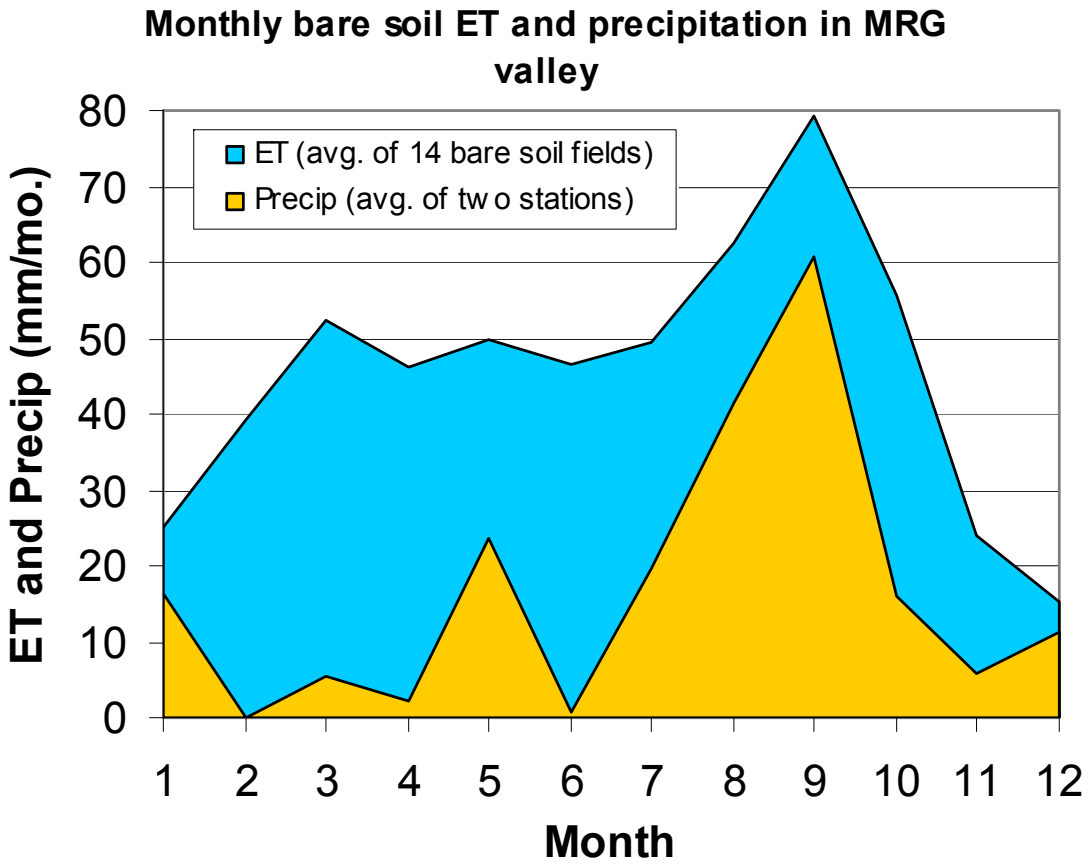
15,000 acres of cottonwood and salt cedar





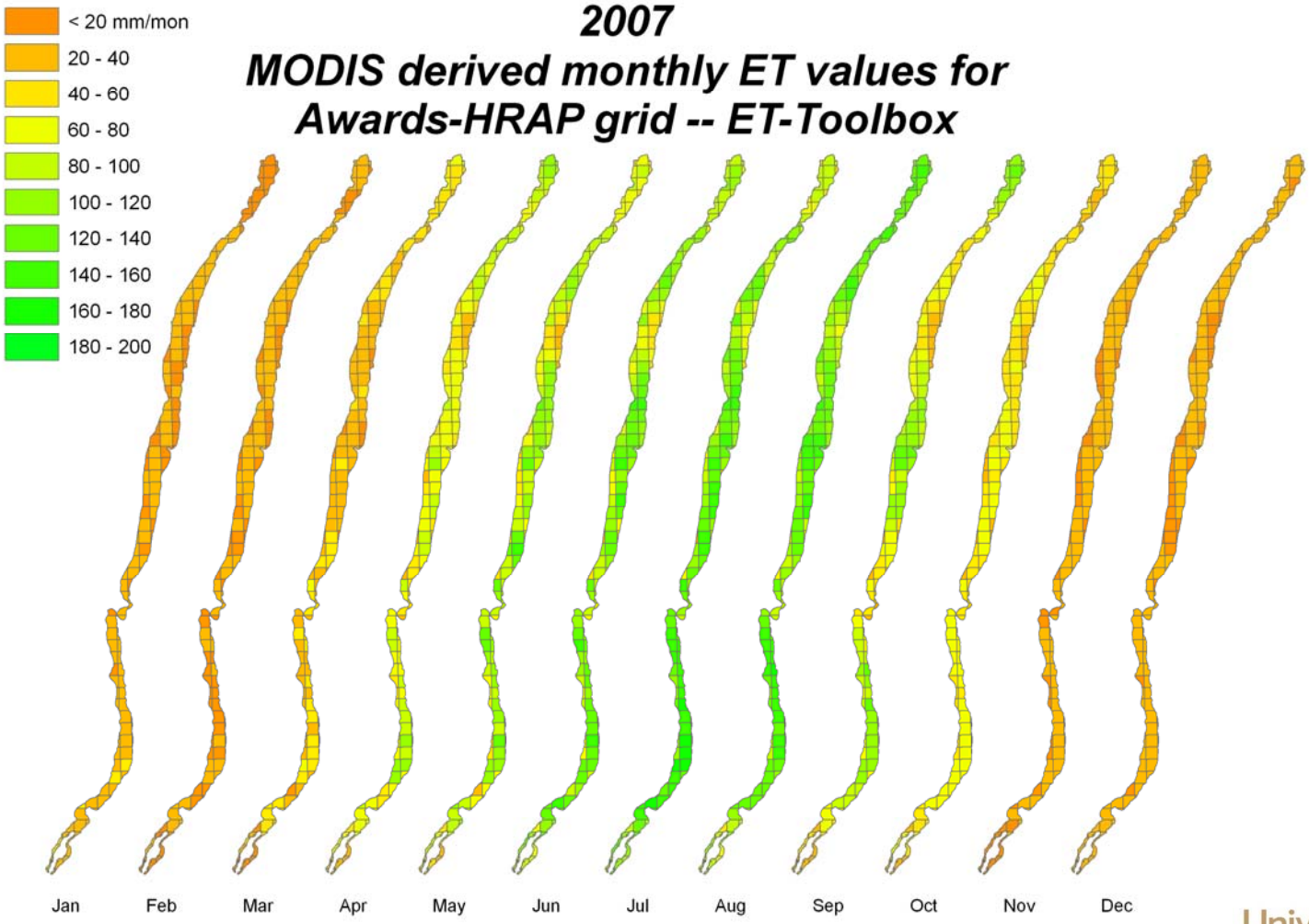
Tasumi and Allen, 2006

With Thermal Imaging, we can see important evaporation from wet soil – for example from high water tables



Evaporation during 2002 from continuously bare areas along the ***Middle Rio Grande*** *of NM contrasted with precipitation*

MODIS based METRIC ET_rF for 26 Image Dates during 2007
Middle Rio Grande Basin, New Mexico



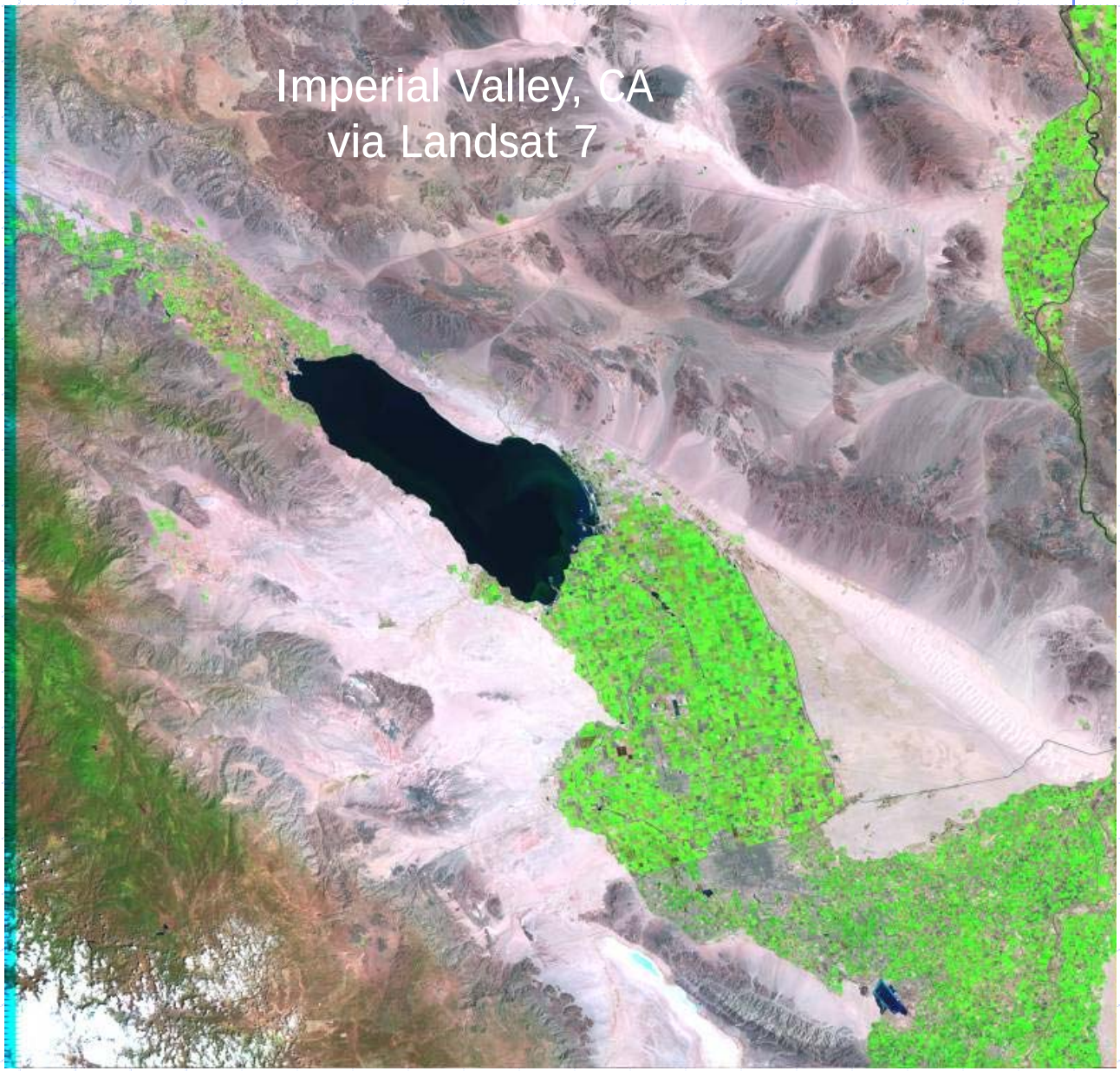
University of Idaho
A LEGACY OF LEADING

MODIS does have merit: frequency – A view angle < 20° each 4 days to capture evaporation from wetting events

California

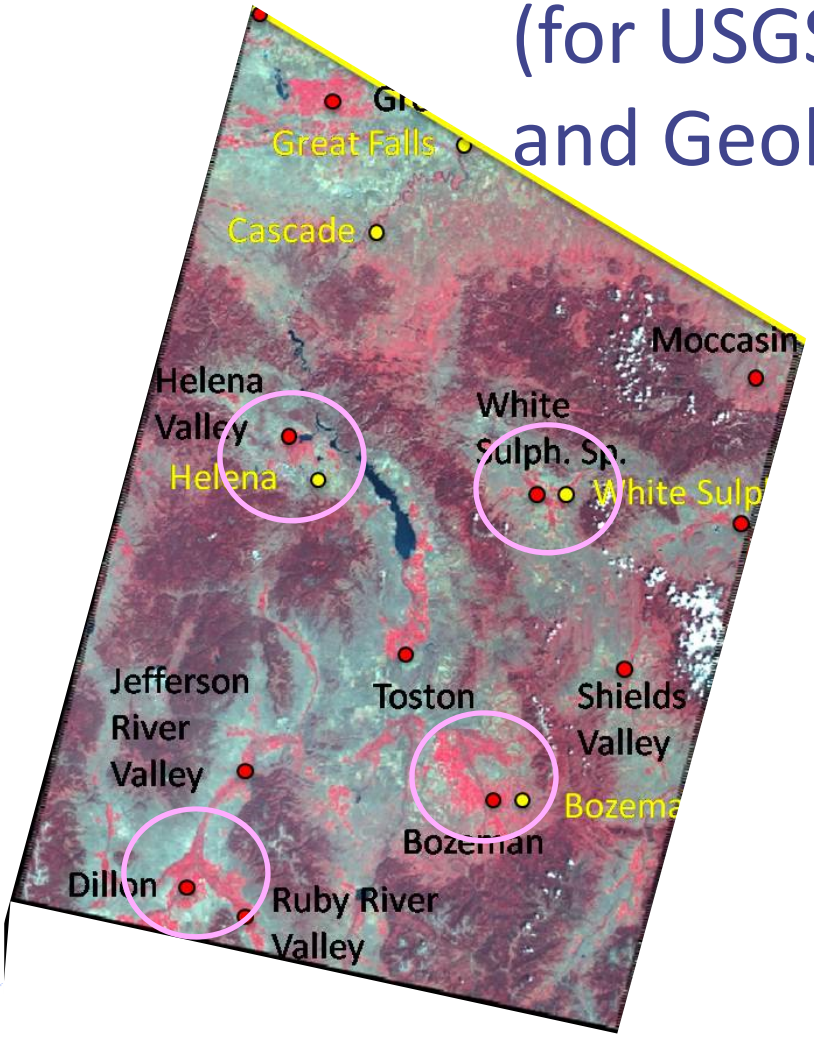
Imperial Valley

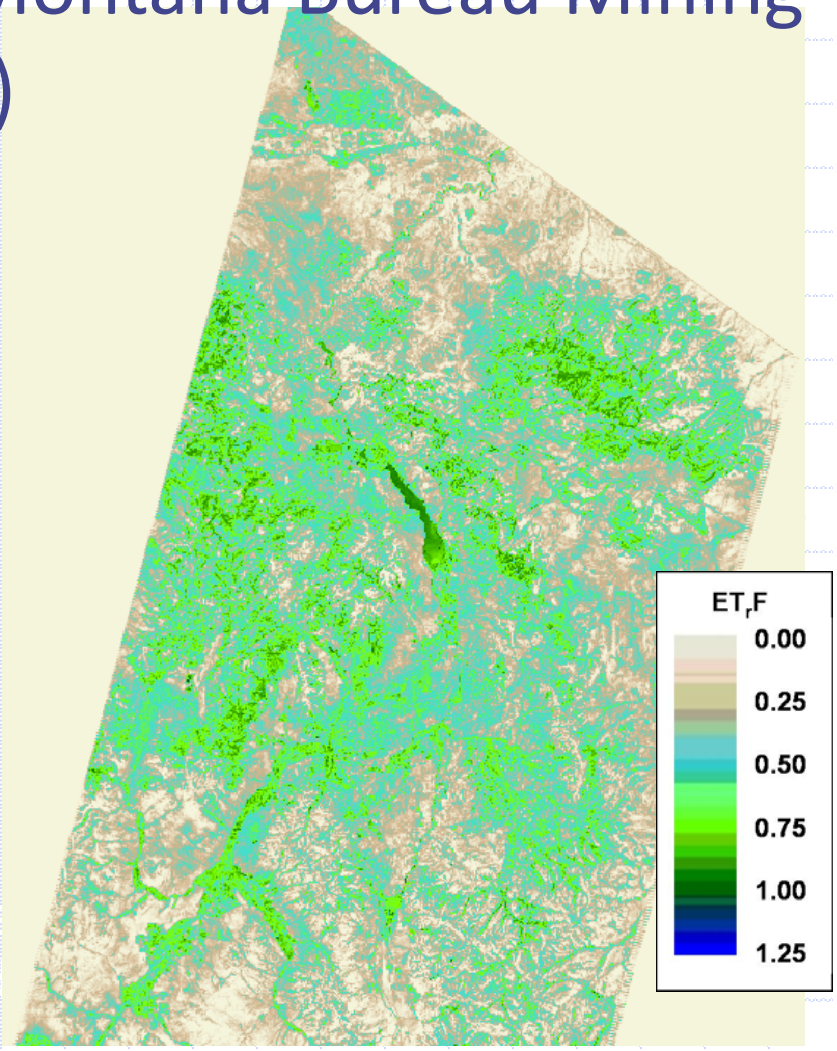
- ~15% of traditional water supply to agriculture will now flow to San Diego/ Los Angeles
- What is the impact on ag. and on the Salton Sea?



Montana

Ground water recharge and water balance in four basins (for USGS / Montana Bureau Mining and Geology)

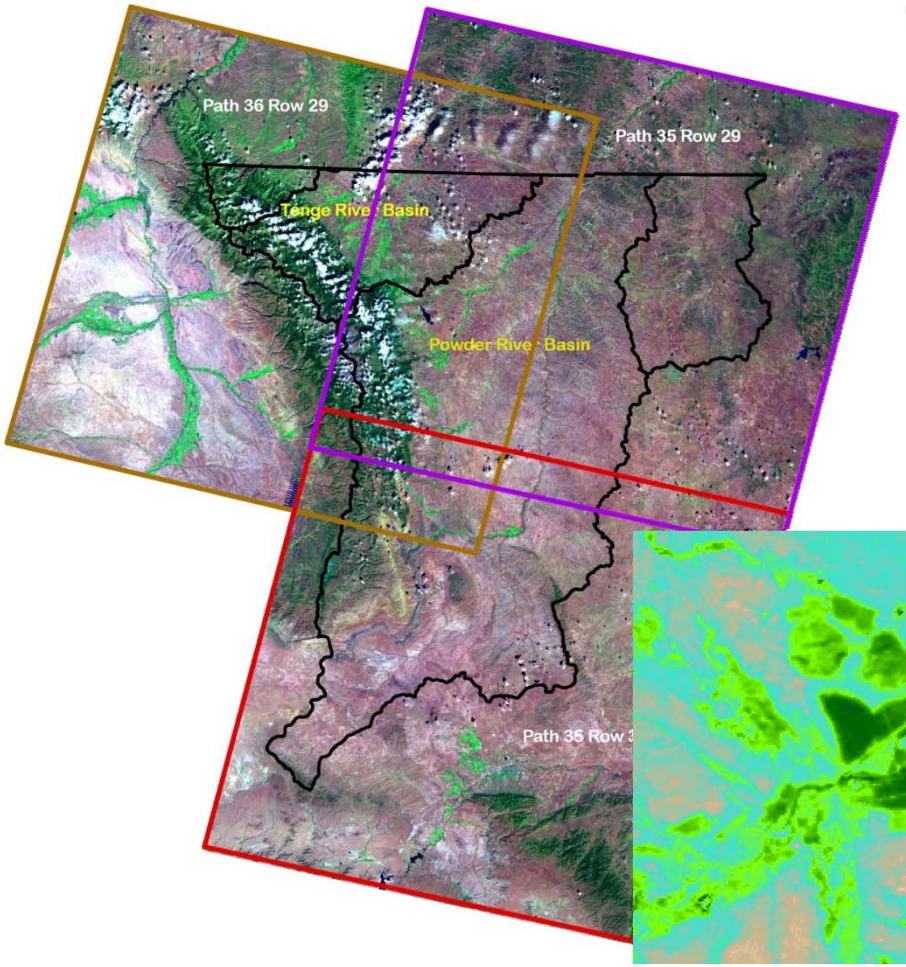




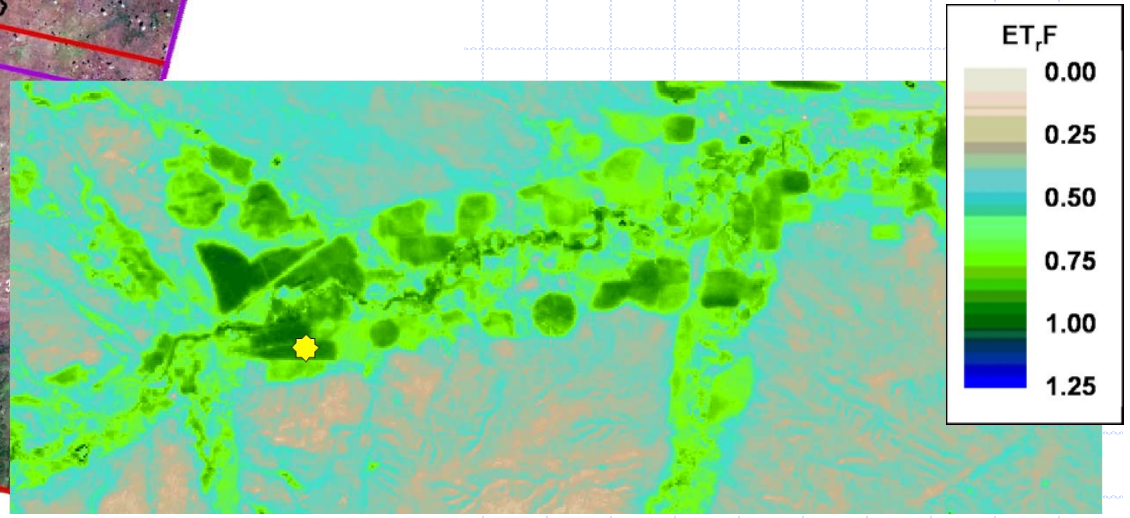
Trezza and Allen, 2008

Montana

Montana v. Wyoming
US Supreme Court
Yellowstone River Basin



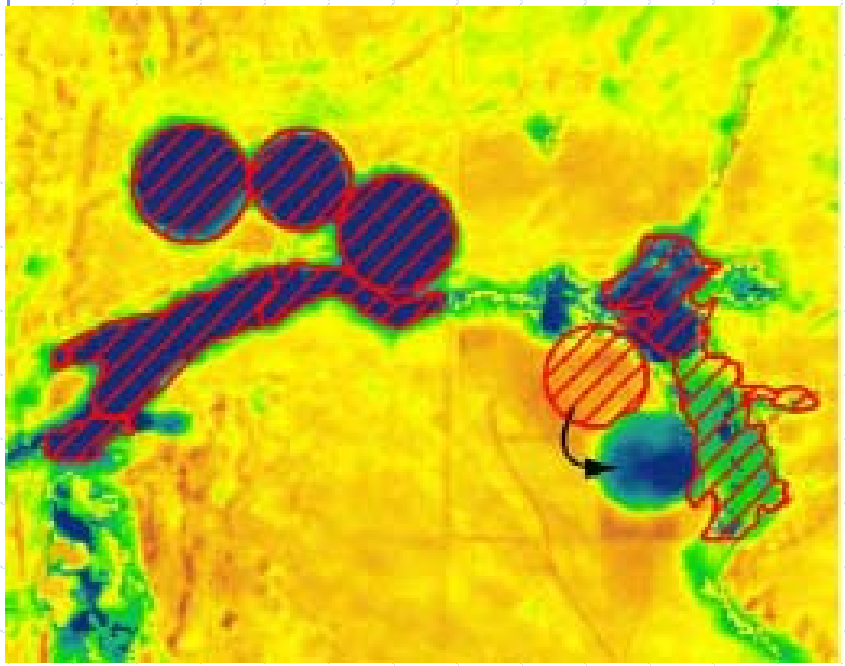
- Issue: Alleged expansion of irrigated area in Wyoming with Depletion of Streamflow to Montana

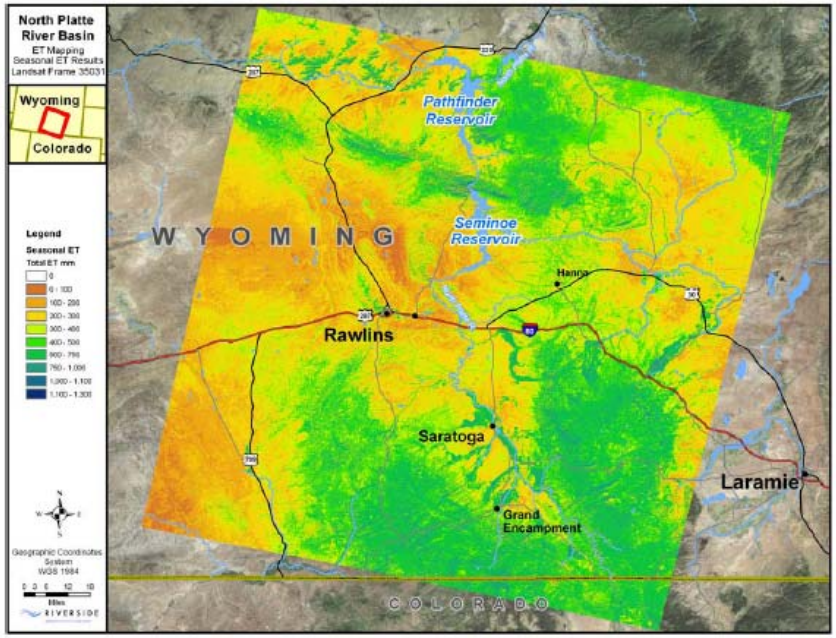


Kelly and Allen, 2008

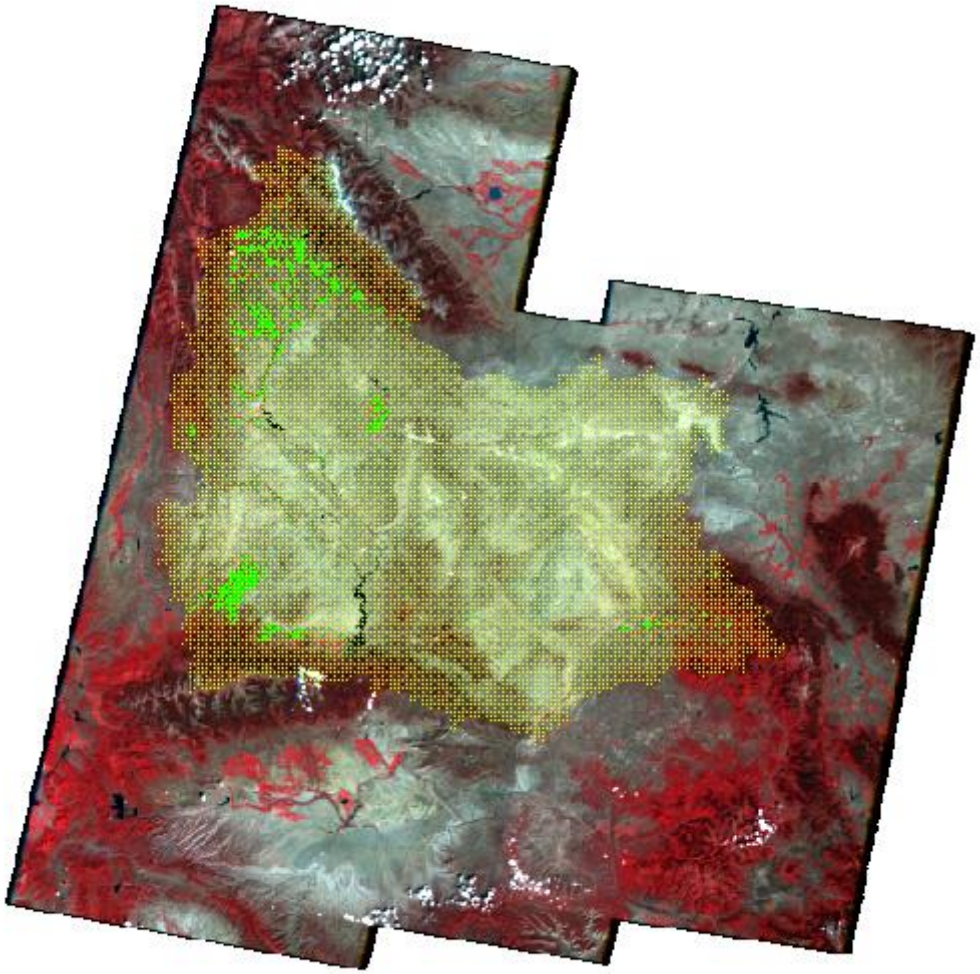
Wyoming

- North Platte Water Decree
  - Nebraska / Wyoming / Colorado settlement in 2001
  - States proportion ET among themselves
  - High resolution monitoring is needed due to narrow irrigation corridors along streams





Wyoming



Allen and Hendrickx, 2013

Green River Basin

Wyoming must self-monitor depletion of the Green River due to irrigation as part of the Colorado River Basin Compact.

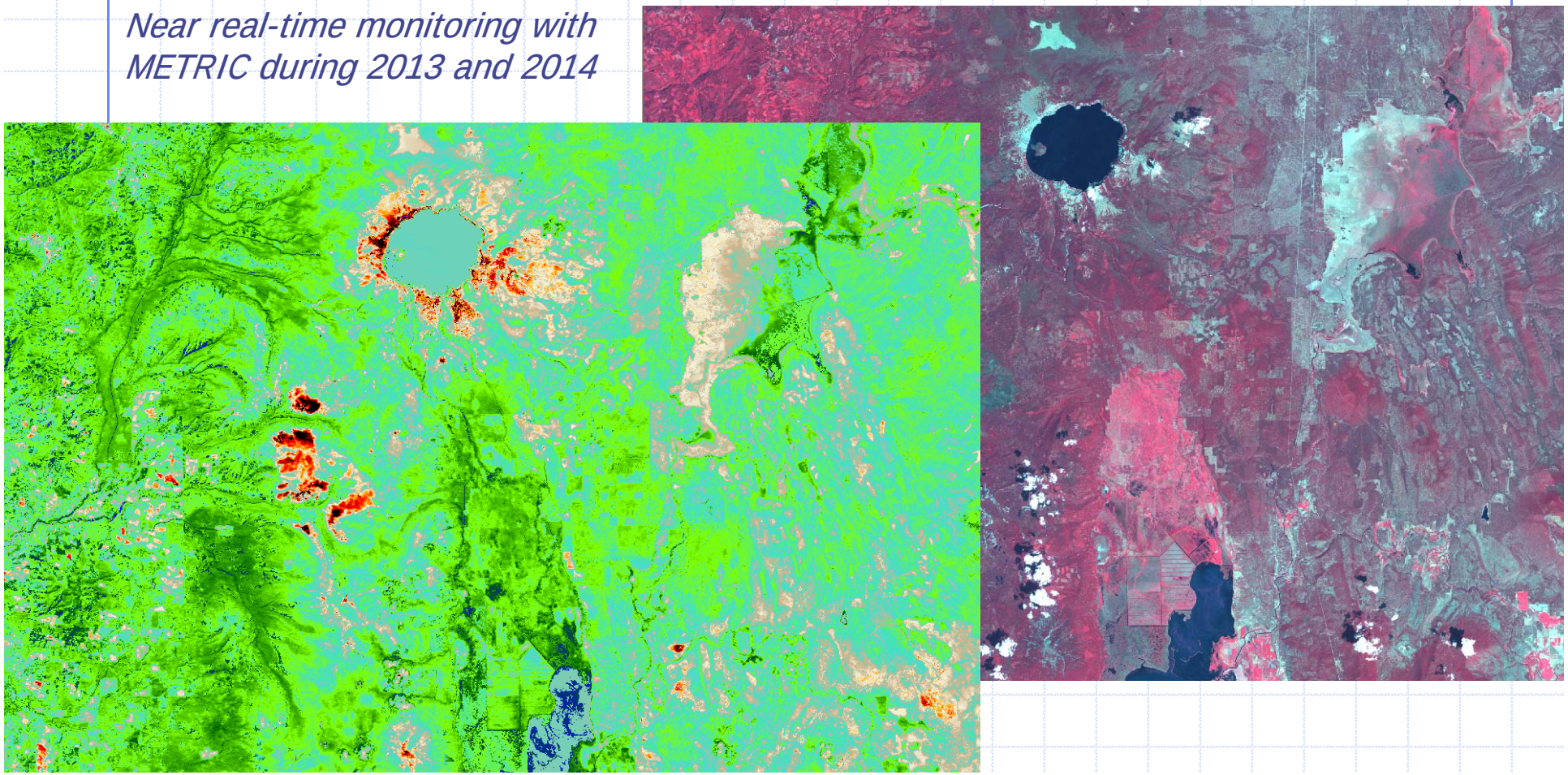
California, Arizona, Nevada have entitlements that must be filled.

High resolution monitoring is needed due to narrow irrigation corridors along streams

Oregon

- Retirement of Irrigated areas in Klamath basin for Endangered Species *(USBR, USGS, State of Oregon, local irrigators, Klamath Tribes)*

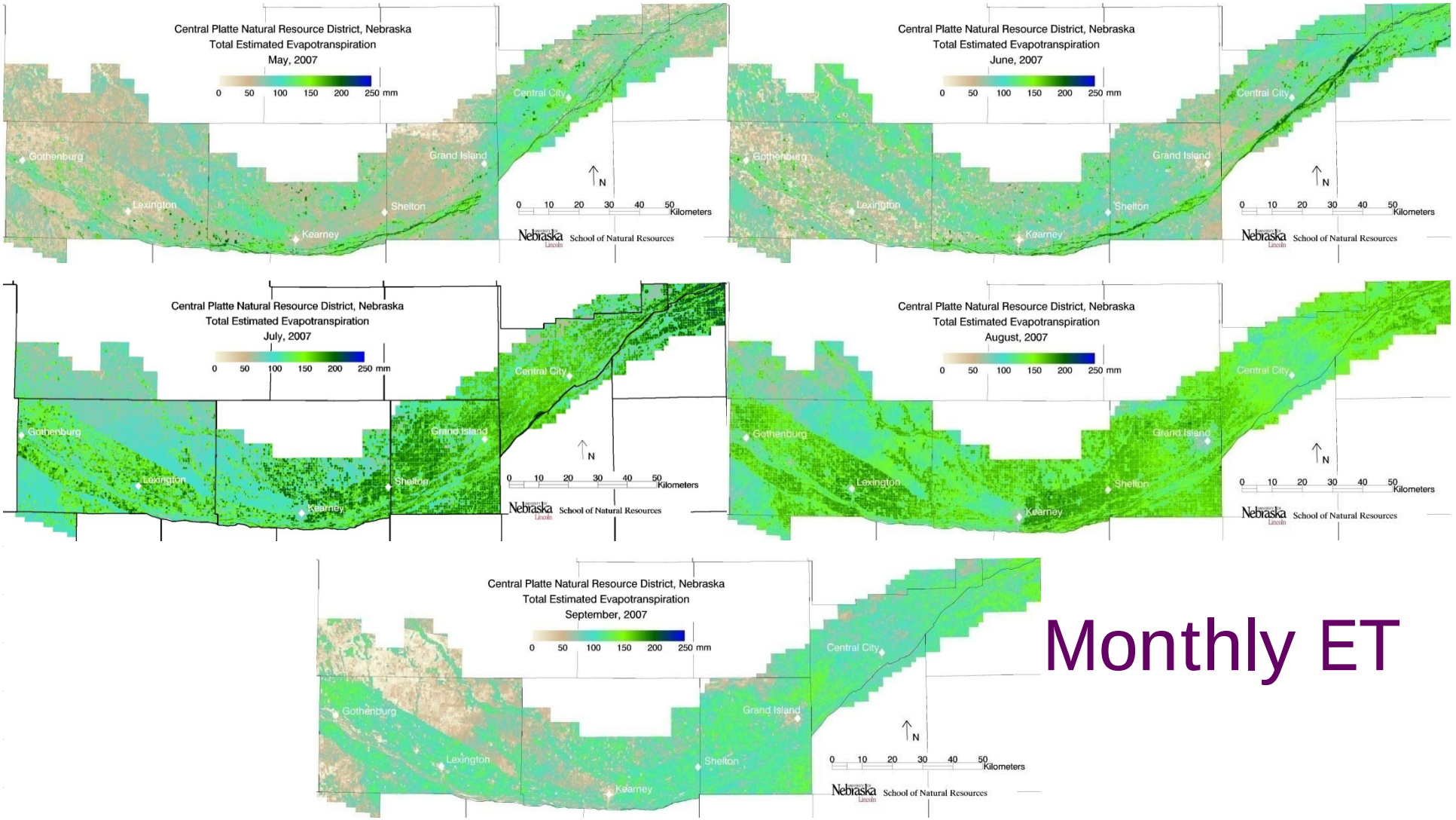
Near real-time monitoring with METRIC during 2013 and 2014



Nebraska

Central Platte Natural Resource District

--- Management of the Ogallala Aquifer



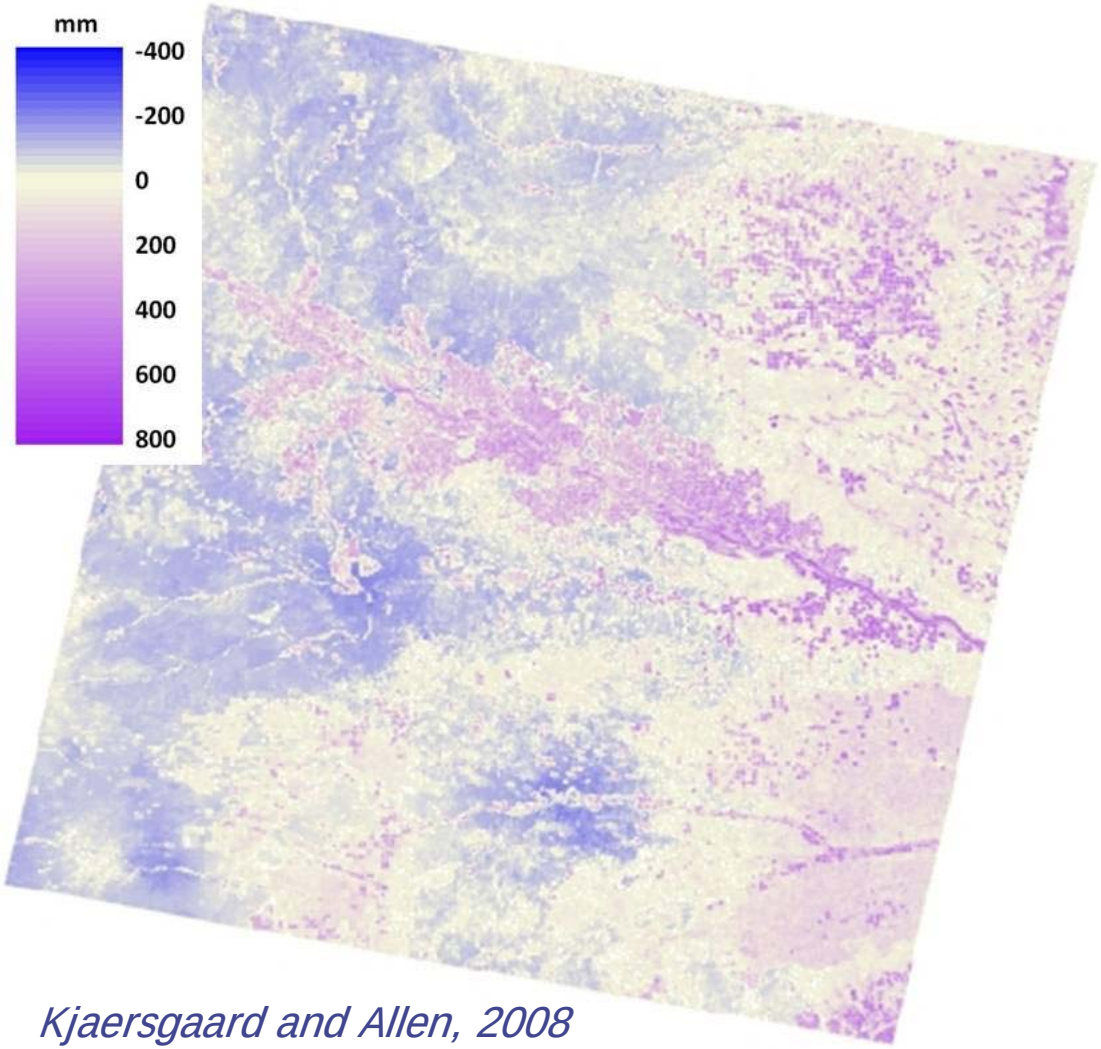
Monthly ET

Dr. Ayse Kilic, UNL

Nebraska

Use ET maps to estimate Recharge
--- Management of the Ogalalla Aquifer

Evapotranspiration minus Precipitation for April 1 – October 31, 1997 for Path 33, Row 31
(Nebraska Panhandle)

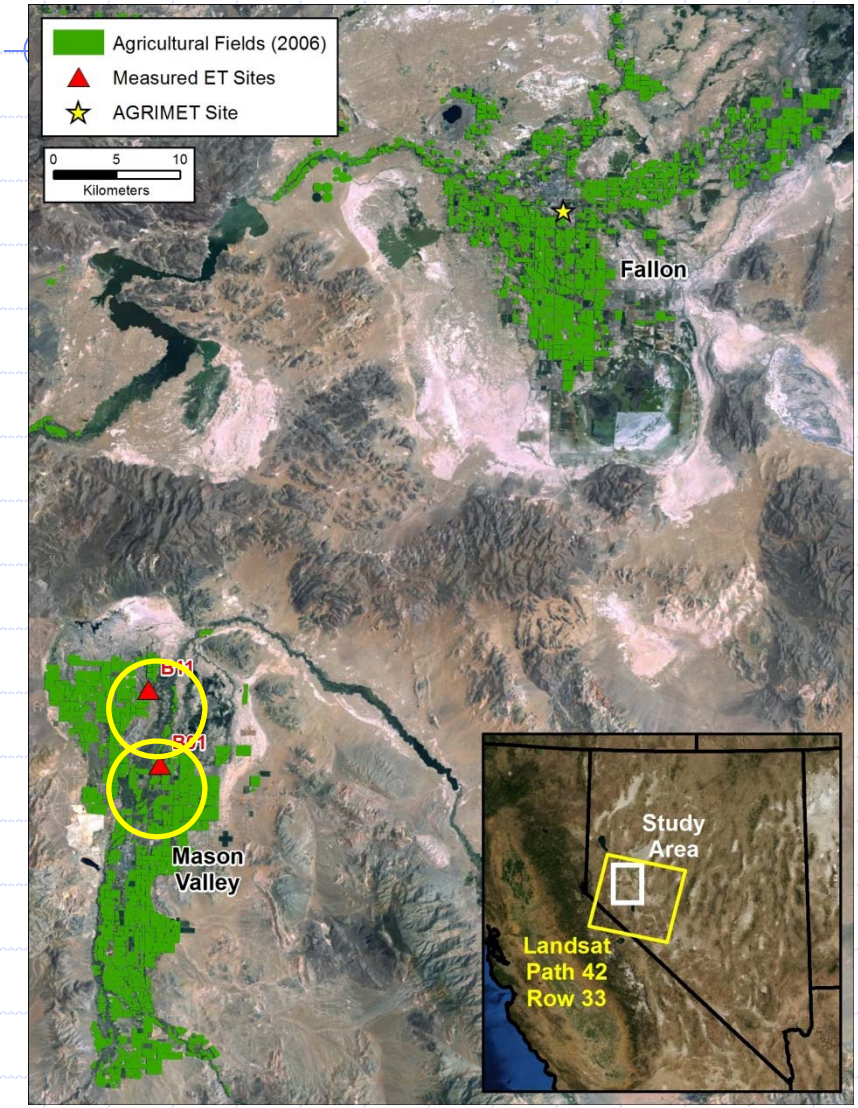


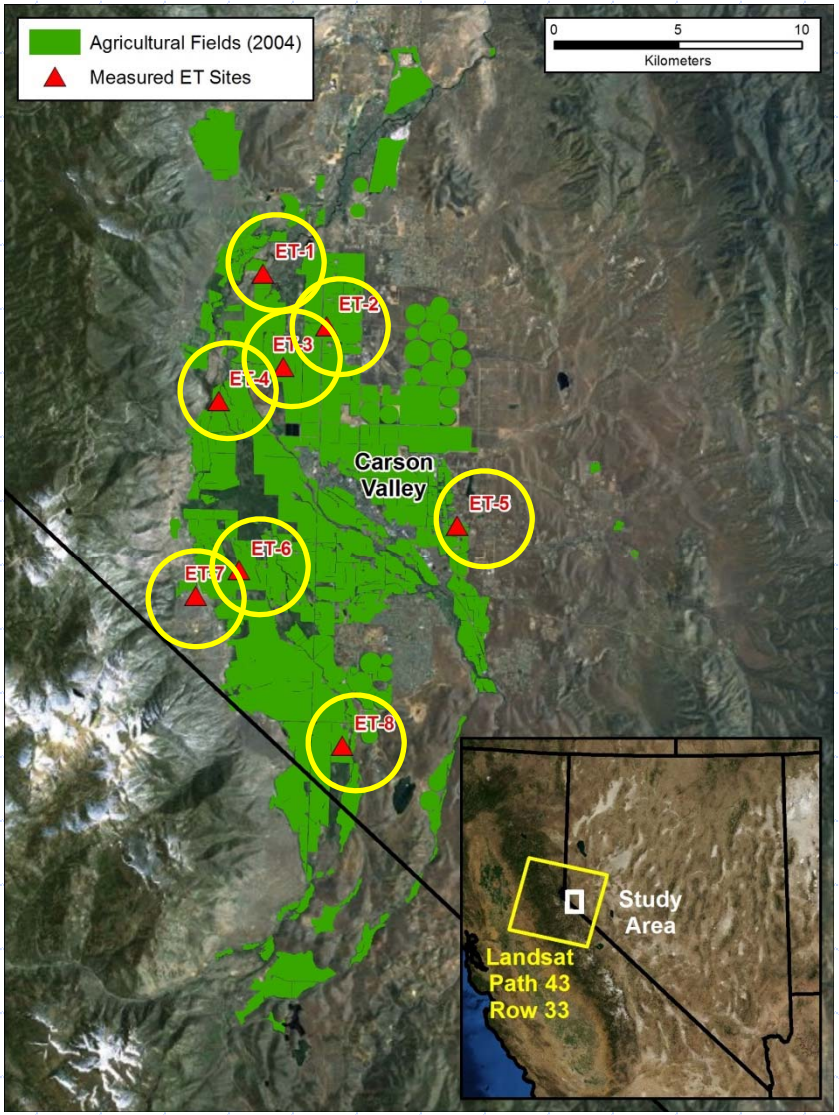
Kjaersgaard and Allen, 2008

Nevada

Dr. Justin Huntington, DRI

Blind Comparison of METRIC Seasonal ET to Measured ET – Desert Research Institute



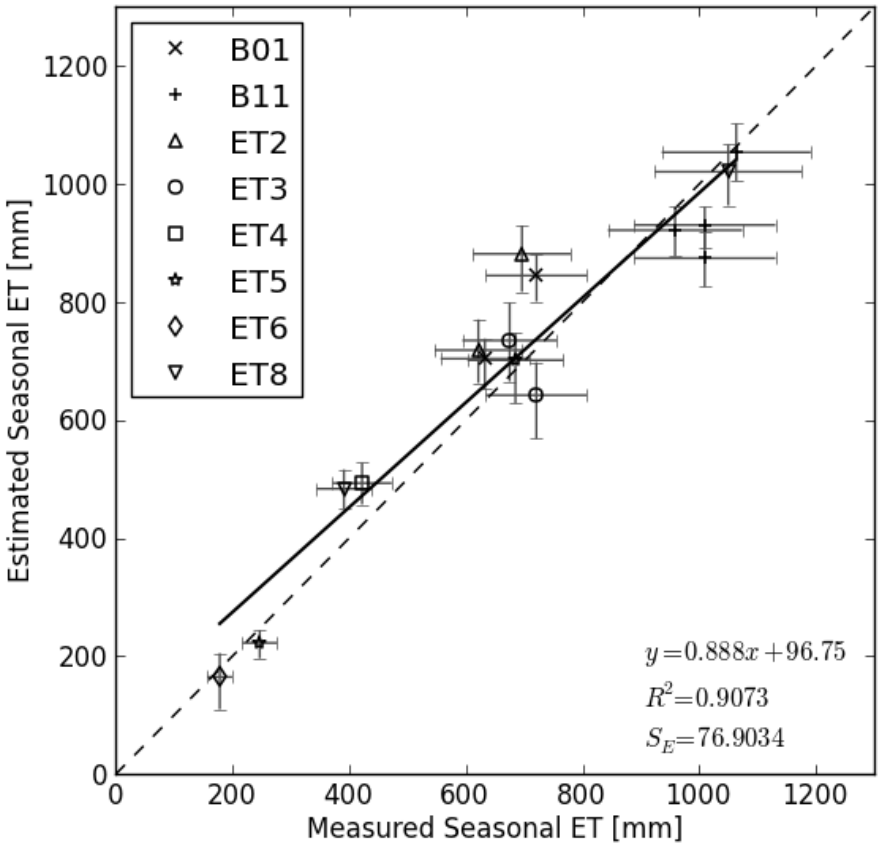


Ground measurement data by USGS

University of Idaho

Nevada

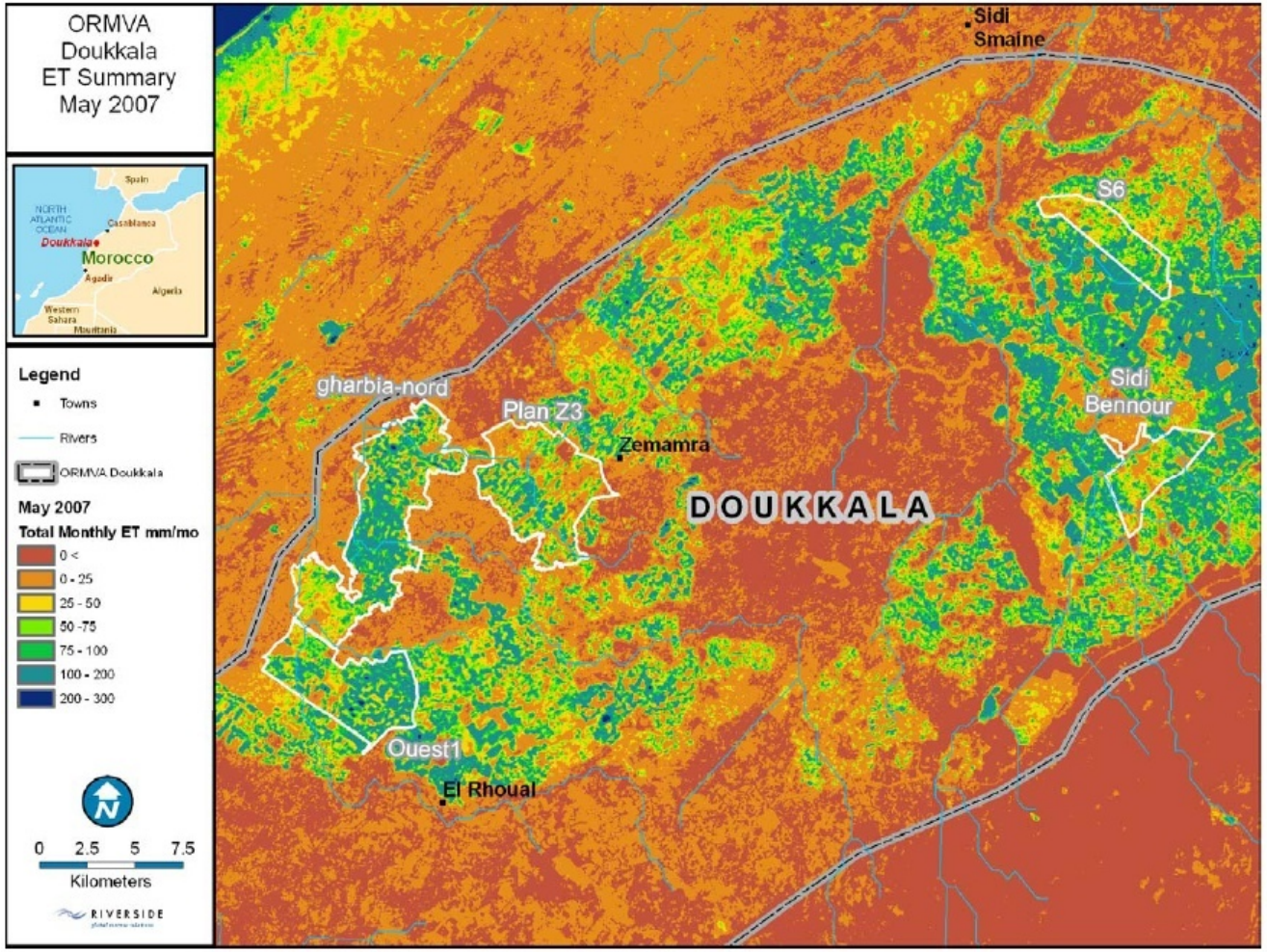
Blind Comparison of METRIC Seasonal ET to Measured ET



- Whiskers on X = +/- 12% USGS estimated uncertainty in measured Bowen ratio/eddy ET
- Whiskers on Y = +/- 95% confidence interval of 100 Monte Carlo METRIC ET estimates

Dr. Justin Huntington, DRI

Morocco



- Poverty reduction program of the World Bank
- Ground-water is overexploited
- ET from satellite can indicate how out-of-balance water use might be
- Better infrastructure may encourage more cash crops
- We can show that conversion to ‘drip’ isn’t going to do it

University of Idaho

2009 Innovations in American Government Award

"Mapping Evapotranspiration from Satellites"

Idaho Department of Water Resources and University of Idaho

Harvard University's Ash Institute

Tony Morse and Bill Kramber, IDWR

HARVARD Kennedy School
ASH INSTITUTE
for Democratic Governance and Innovation

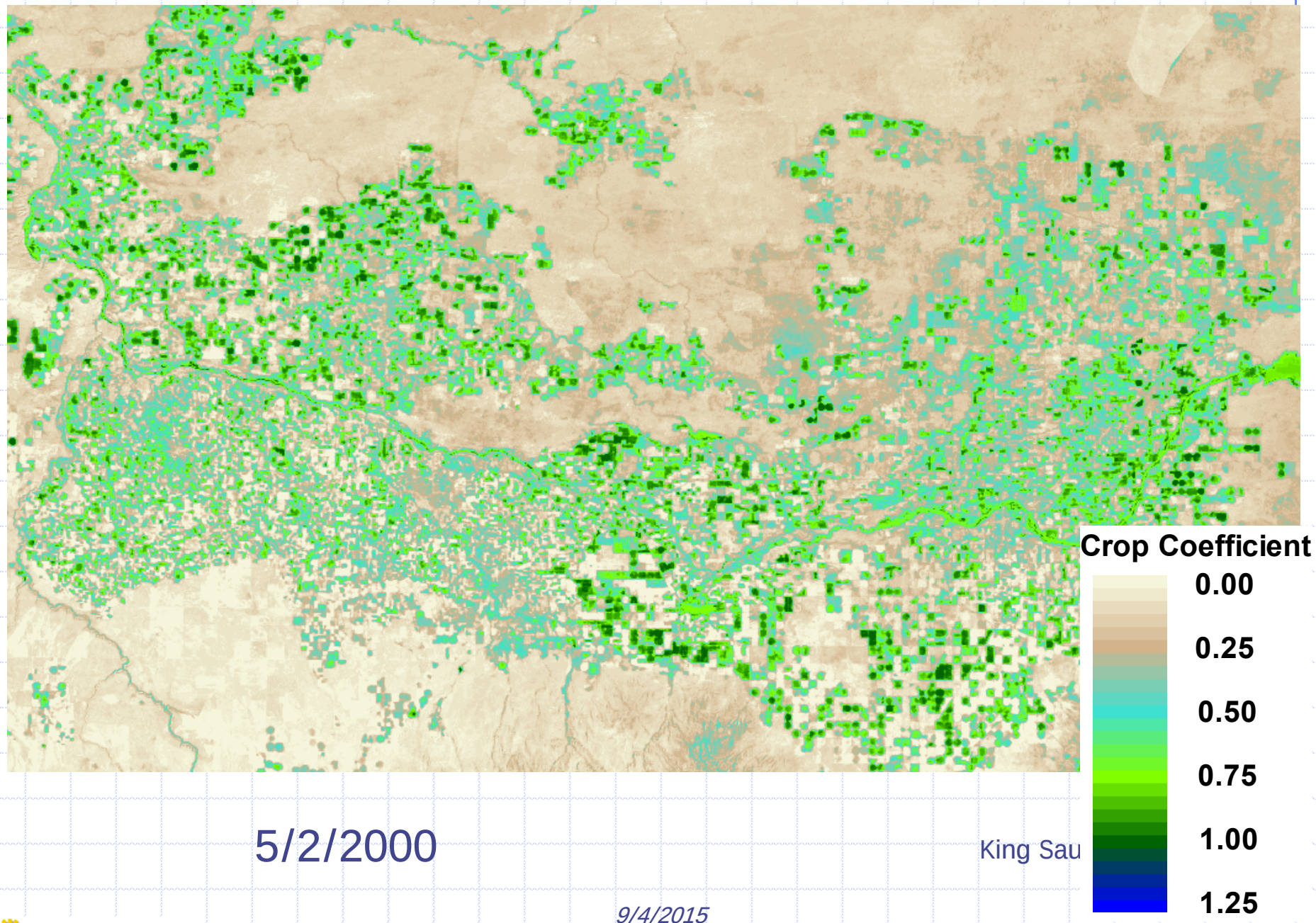
Quotes from Harvard's Site Visit Report to IDWR--

- "Remarkably, METRIC [Landsat] enables Idaho DWR analysts and administrators to measure ET across large expanses of both **space and time.**"
- "METRIC [Landsat]....is **measurably more accurate, fast, and cost-effective** than the traditional, cumbersome, slow and expensive methods that were commonly used in the last century."
- "...it would be **practically *impossible* to adjudicate water rights disputes in the future without [Thermal Images]**."
- "It is measurably effective in that it has distinctive capacities to monitor evapotranspiration and **consumptive water use across both space...and time (..with the help of historic Landsat thermal images)**."

Thank you.

Extra slides

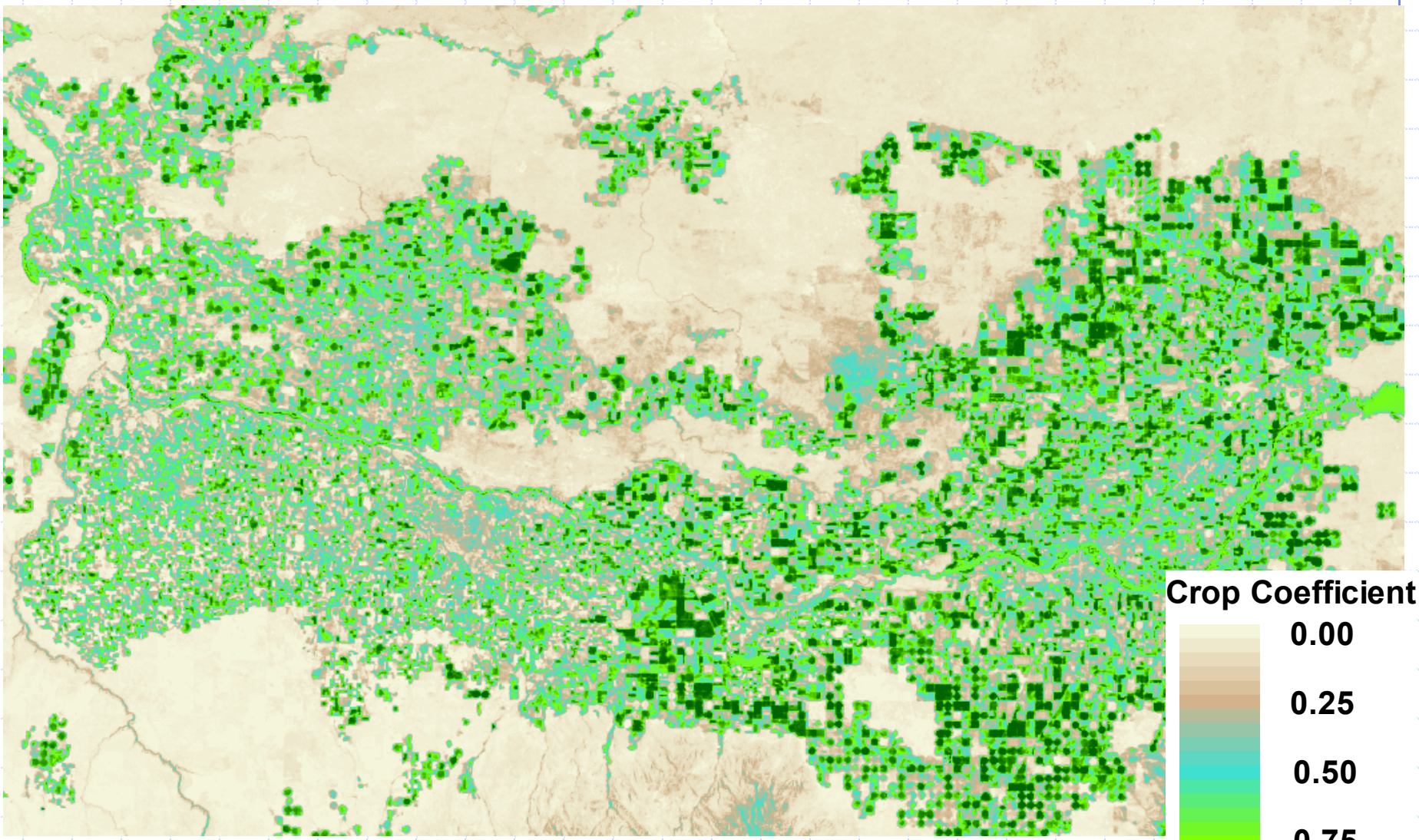
Time Series of Crop Coefficients near Twin Falls, ID



5/2/2000

King Sau

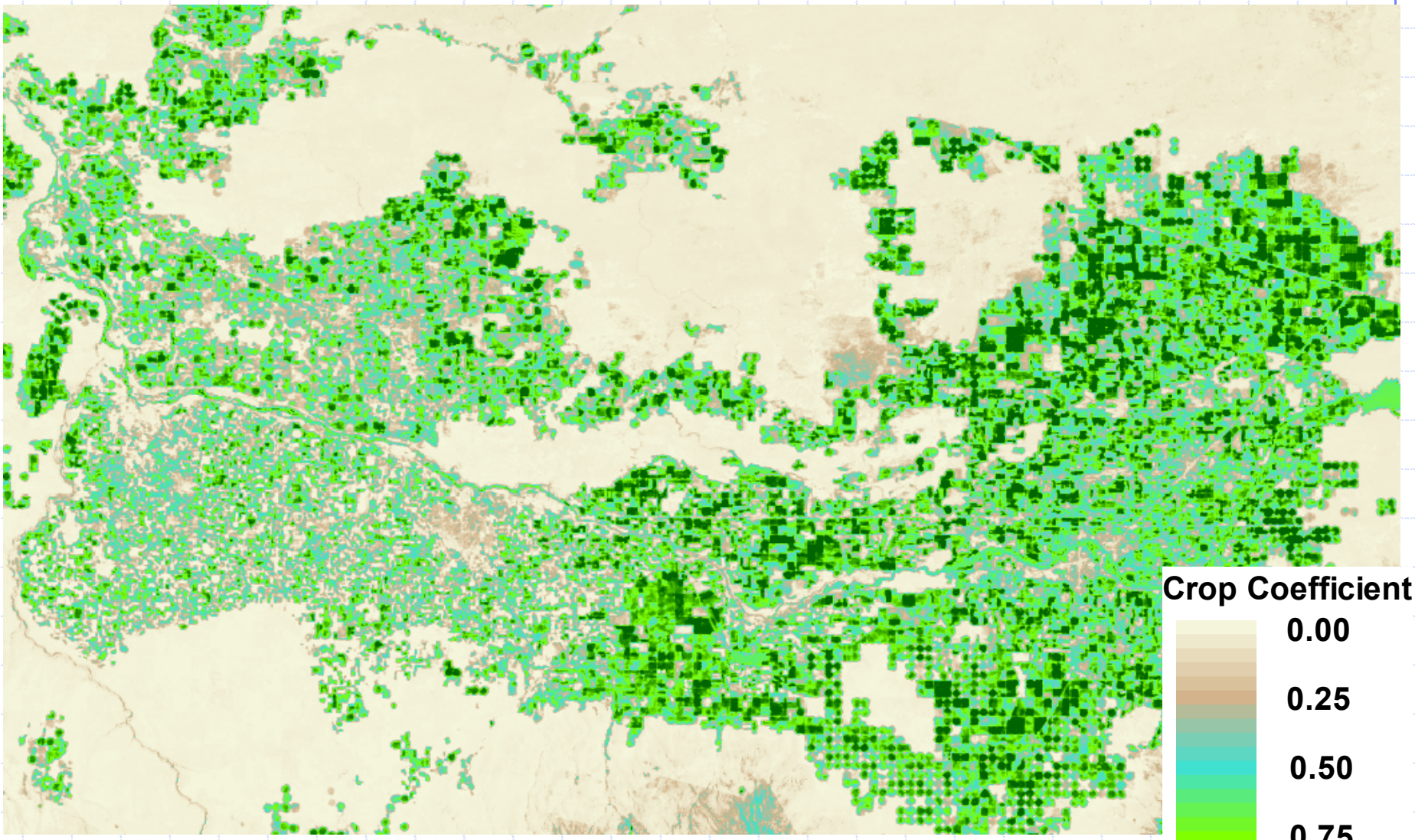
University of Idaho



6/3/2000

King Sau

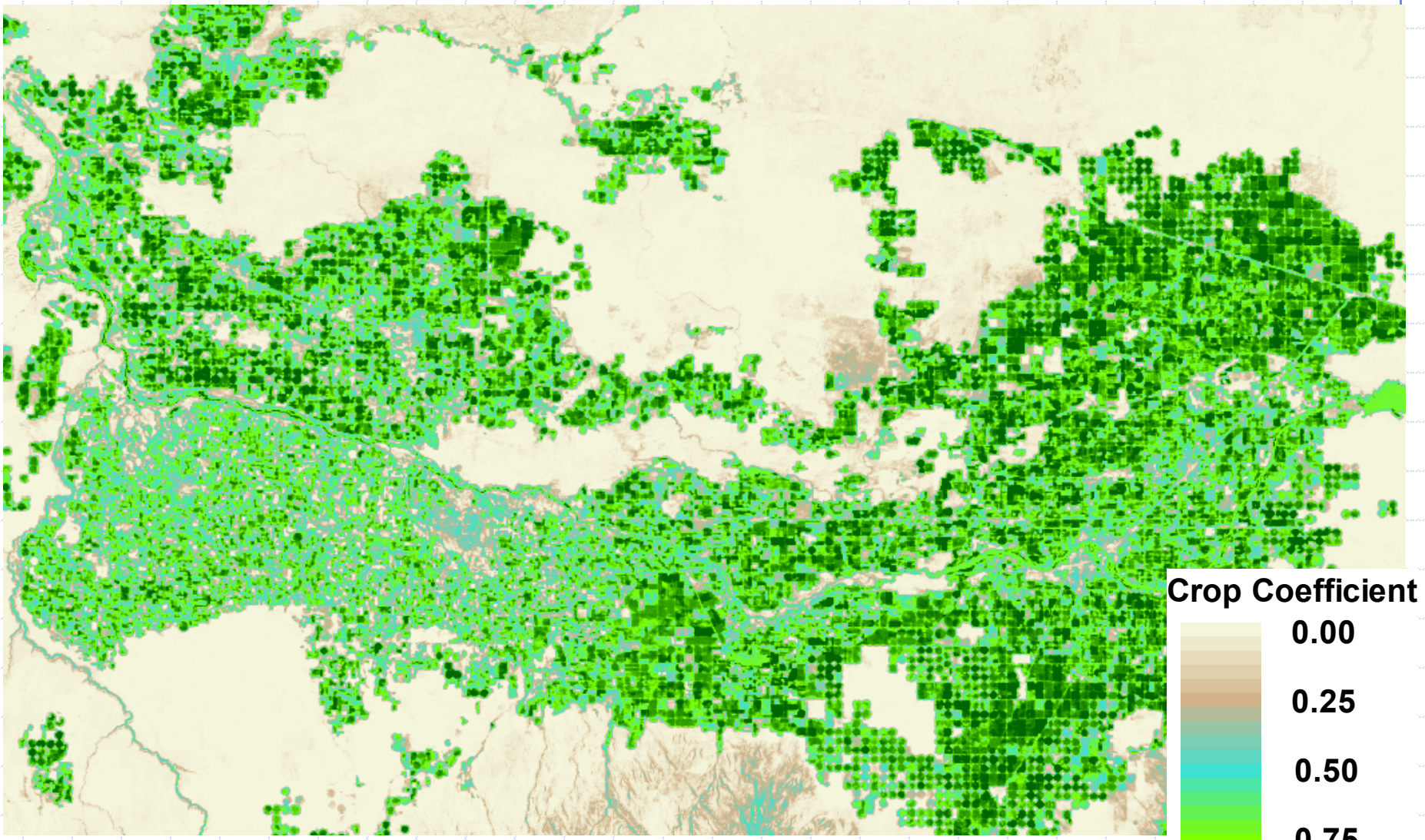
University of Idaho



6/19/2000

King Sau

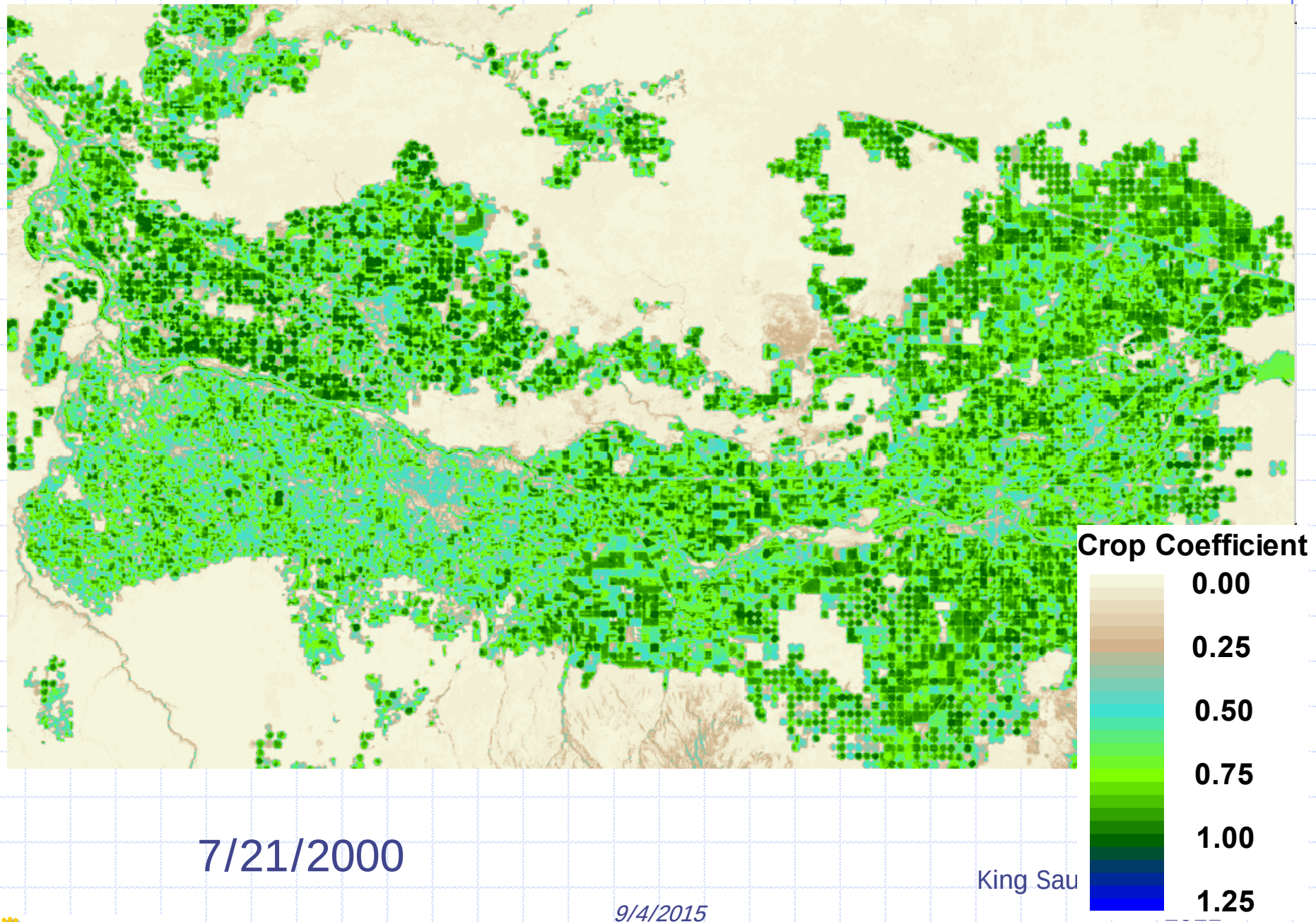
University of Idaho



7/5/2000

King Sau

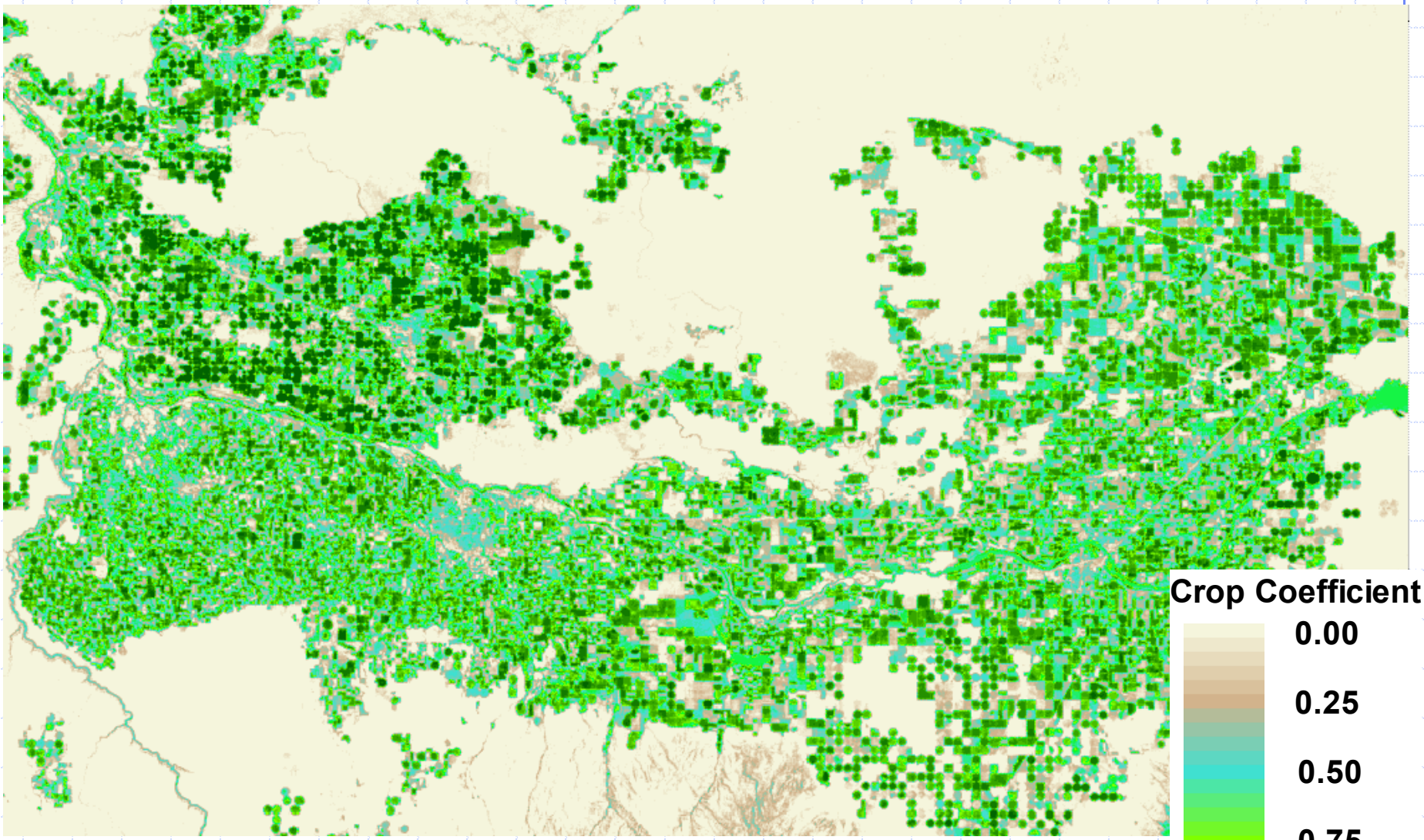
University of Idaho



7/21/2000

King Sau

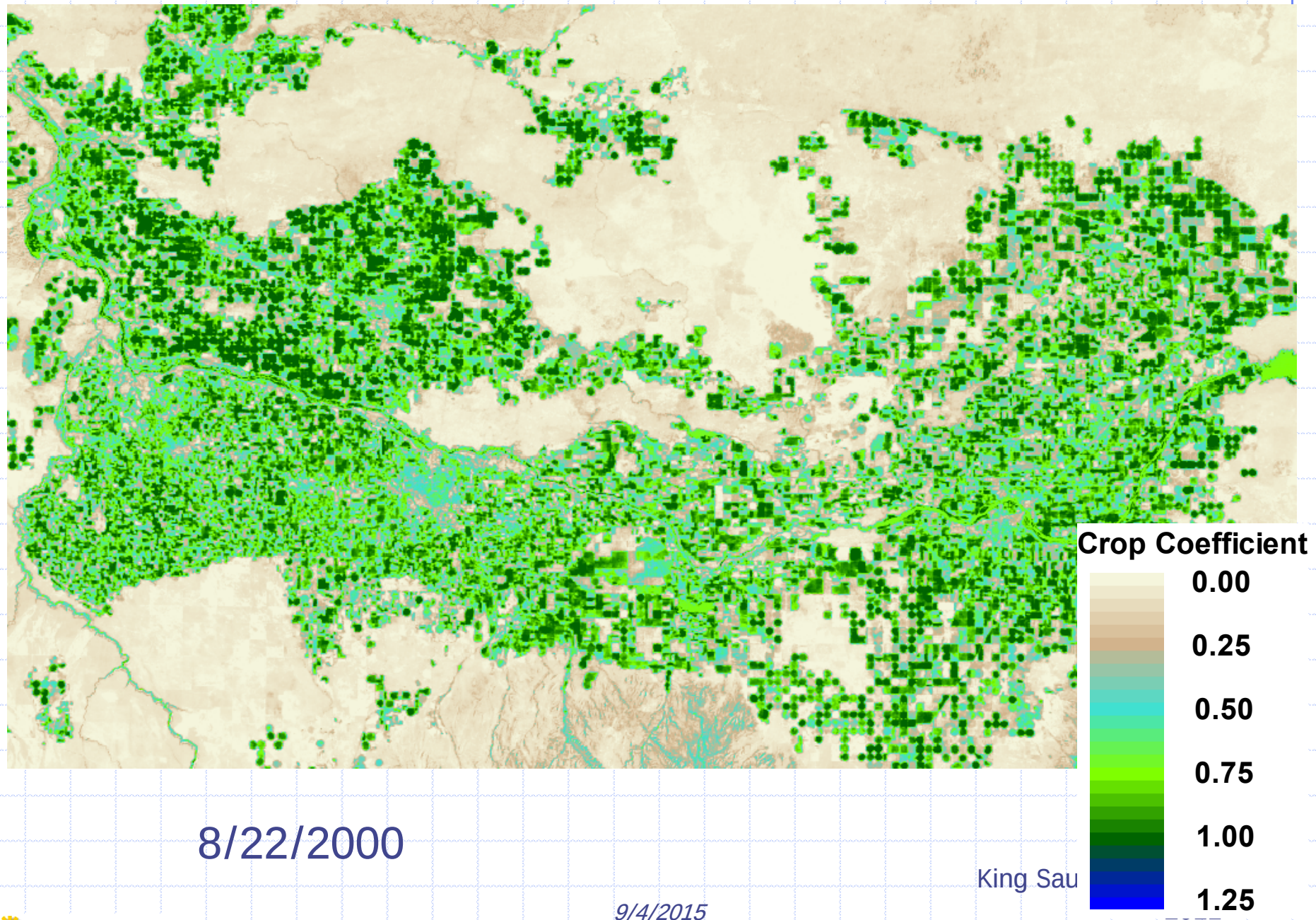
University of Idaho



8/14/2000

King Sau

University of Idaho



8/22/2000

King Sau

University of Idaho

ET Investigations involving METRIC/Landsat -- Applications for Water Management

University of Idaho and Associates/Partners

Richard Allen (UI), Ricardo Trezza (UI), Bill Kramber (IDWR), Tony Morse (SAG), Jan Hendrickx (NMT), Ayse Irmak (UNL), Justin Huntington (DRI), Clarence Robison (UI), Carlos Kelly (UI), Jeppe Kjaersgaard (UI), Jeremy Greth (UI), Masahiro Tasumi (UI), Tim Martin (RTI)

UI: University of Idaho
IDWR: Idaho Department of Water Resources
SAG: Spatial Analysis Group (Morse)
NMT: New Mexico Tech
UNL: University of Nebraska, Lincoln
DRI: Desert Research Institute

RTI: Riverside Technologies, Inc, Fort Collins CO
SHA: Soil Hydrology Associates, Los Lunas NM (Hendrickx)
MDNRC: Montana Department of Natural Resources and Cons
OSE: Office of State Engineer
NRD: Natural Resource District

ET+: Evapotranspiration Plus, Twin Falls ID (Allen)
MBMG: Montana Bureau of Mining and Geology
SNA: SEBAL North America
NMSU: New Mexico State University
CSU: Colorado State University

Flathead Valley, MT

Yakima River Basin -- calibration of large scale energy balance models for assessing climate change. (Univ. Wash.)

Flathead Indian Reservation -- irrigation water consumption for managing streamflows (UI for MDNRC)

Klamath Basin -- water for grazing and local ecosystem interactions, ground water balance, irrigated areas (UI, ET+ for USGS, USFS)

Ground water recharge estimation in four basins: Helena, White Sulpher Springs, Dillon, and Bozeman. (UI for USGS, MBMG)

Lemhi River -- irrigation management for salmon recovery (IDWR, UI for IDWR)

Green River/Upper Colorado River (UWYO, SHA, RTI, ET+ for WY-OSE)

Boise River Valley -- agricultural to urban land use change (IDWR for IDWR)

IDWR

Richard Allen
University of Idaho

Upper North Platte -- water decree compliance (RTI, ET+)

Ogallala aquifer -- ground water management, mitigation and Riparian ET (UNL, UI for NRDs)

Central Iowa -- ET from Agriculture (USDA-ARS, UI)

Justin Huntington
DRI

Eastern Snake Plain -- irrigation transfers, ground water model calibration (UI for IDWR)

Tim Martin
RTI

Ayse Irmak
UNL

Central Nebraska -- comparison to measured ET (UNL)

Bear River -- Interstate Compact (UI for IDWR)

South Platte -- conjuctive management of ground water and surface water (RTI, UI)

Owens Valley -- ET of Desert (NMSU)

Western Nevada -- water transfers between irrigated agriculture, municipalities, and playas. (DRI, UI, NV-OSE for NV-OSE)

Arkansas River -- assessment of water shortage and salinity impacts (CSU)

Middle Rio Grande -- water consumption by invasive vegetation (UI for USDOJ)

Imperial Irrigation District - impacts of water conservation measures, salinity, and timing of ET (UI, SHA)

Jan Hendrickx
NMT

Lower Rio Grande -- water use by irrigated agriculture (NMSU, UI, for NM-OSE)

Palo Verde Irrigation District - intercomparison of ET methods (USU, USGS, USBR, UI)

Amarillo Area (USDA-ARS, UI)

Lubbock Region (SHA)

Martha Anderson
USDA-ARS

Tampa Bay Water (ET+ for TBW)

Upper North Platte River, WY

Southern Idaho Fields

Imperial Irrigation District, CA

Walker River, NV

Middle Rio Grande, NM

Eastern Snake Plain, ID

Landsat

MODIS

Minidoka, ID

Tampa Bay Area, FL

University of Idaho
A LEGACY OF LEADING