Using Earth Observation in Crop Yield Modeling: Latest Development

Part(1): EO in Crop models: Mechanistic and/or Empirical

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ARC-ISCW, Geoinformation Science Programme

→**P**lant system and yield complexity

→**Y**ield estimation and EO systems

→**E**mpirical models

→**M**echanistic models

→**C**ombined models

→**M**odels Classification

→**EO** sensors for plant monitoring

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$Crop\ Yield$:

$\int ET \uparrow$

$\int Rainfall + Irrigation \downarrow$

$\int Radiatio$

$\int Temperature$

$\int Nutrients$

$\int Cu$

$\int Manageme$

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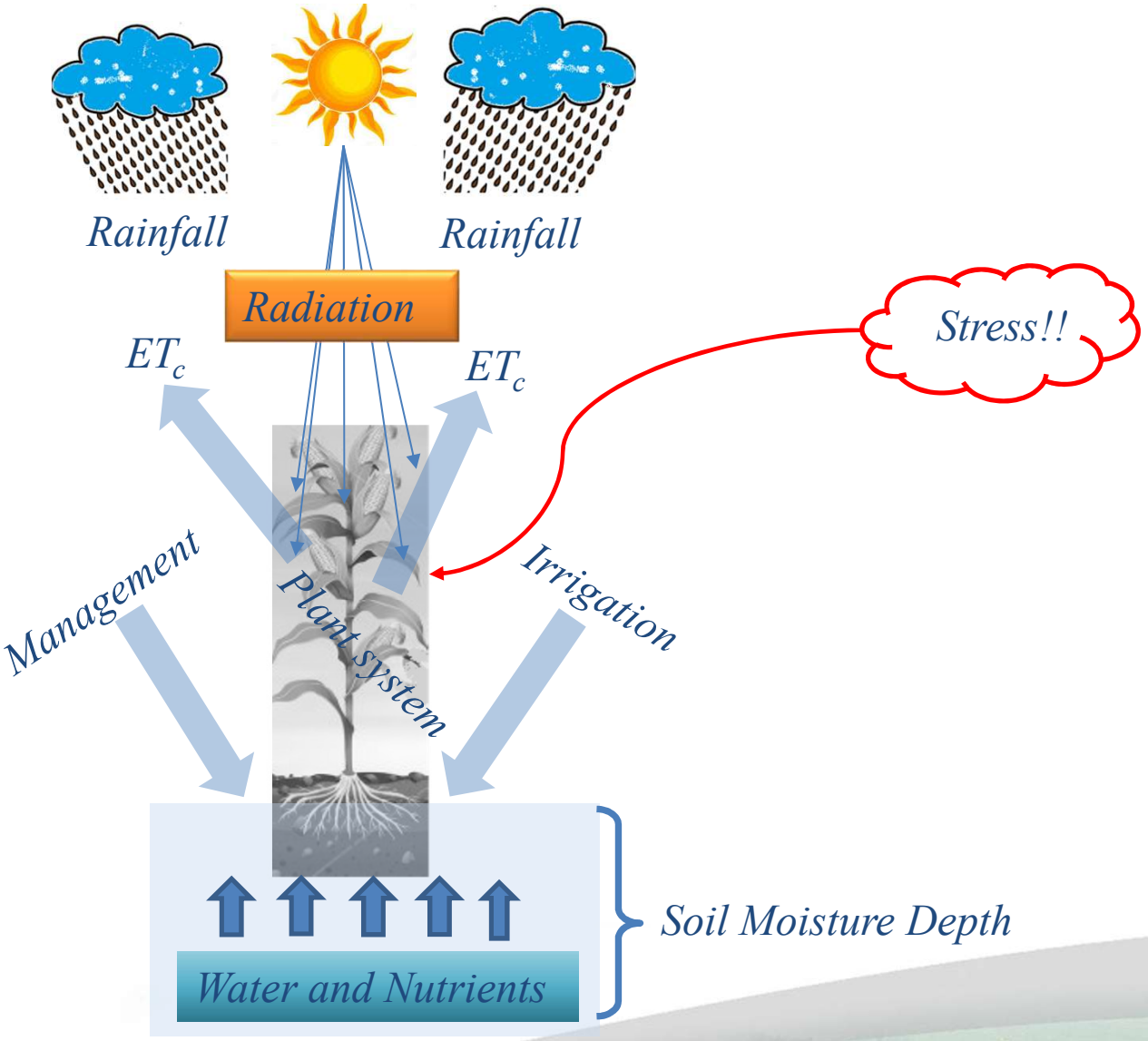
$\int e$



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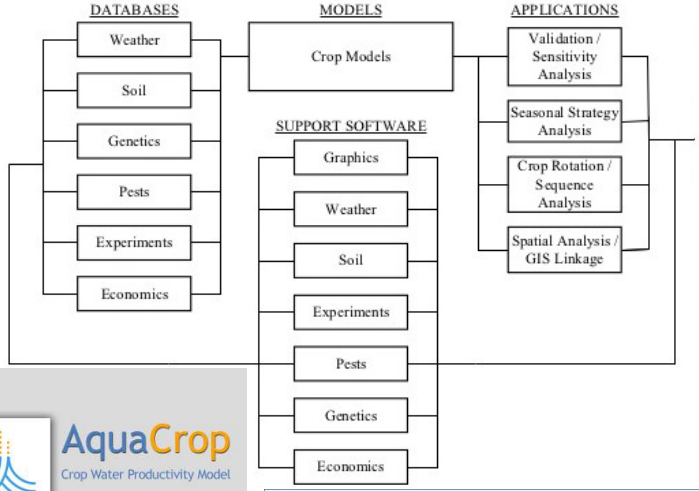


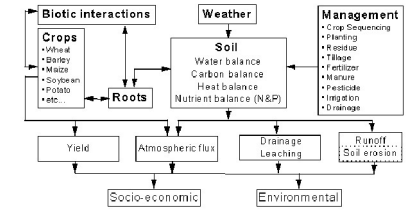
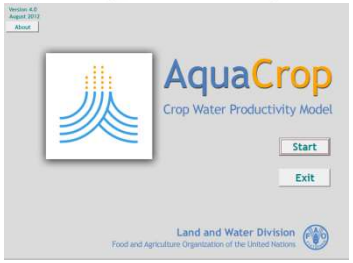
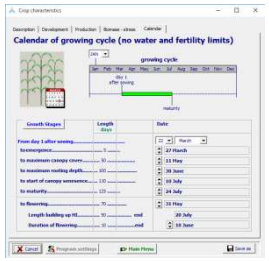
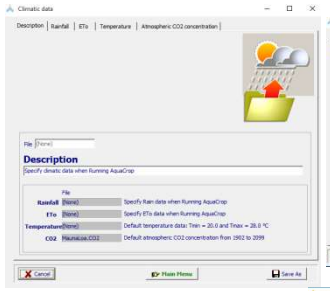
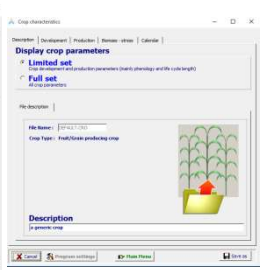


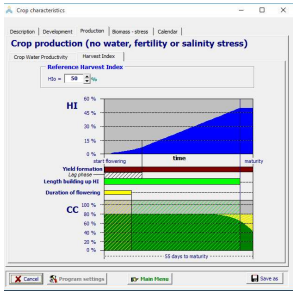
Figure 1. Diagram of the components of SALUS.

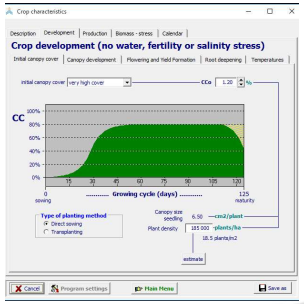


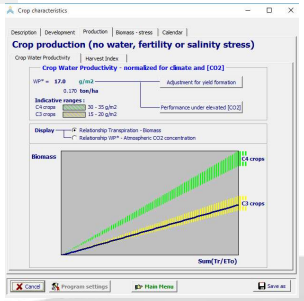


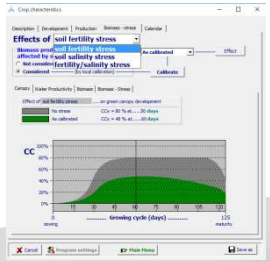


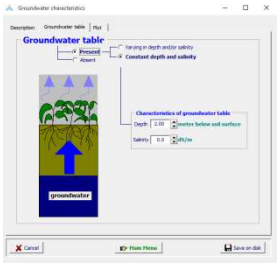


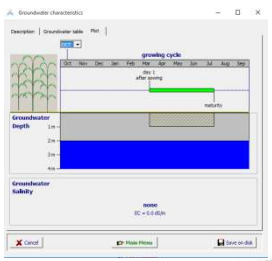


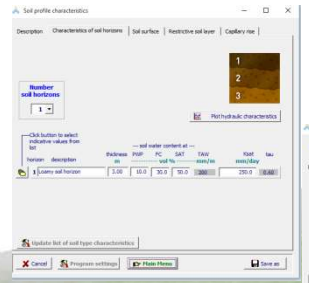


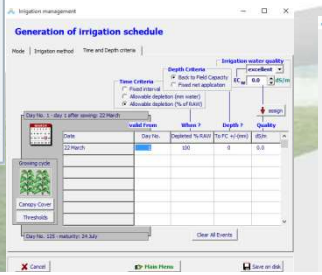


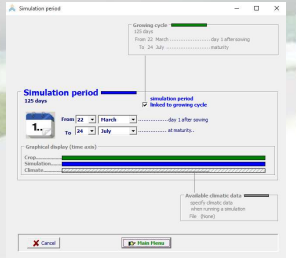












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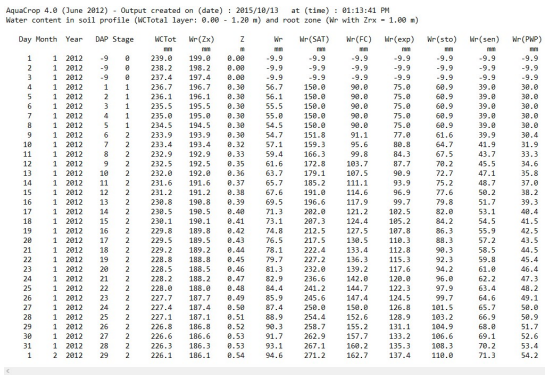
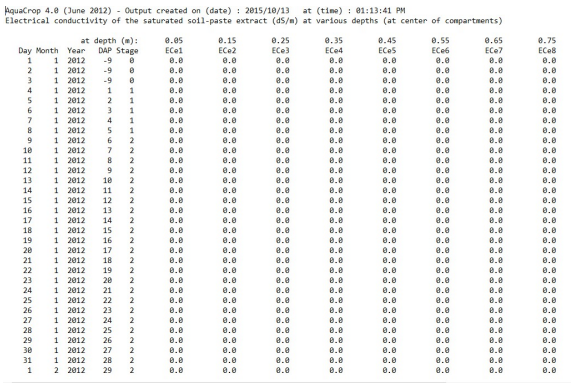


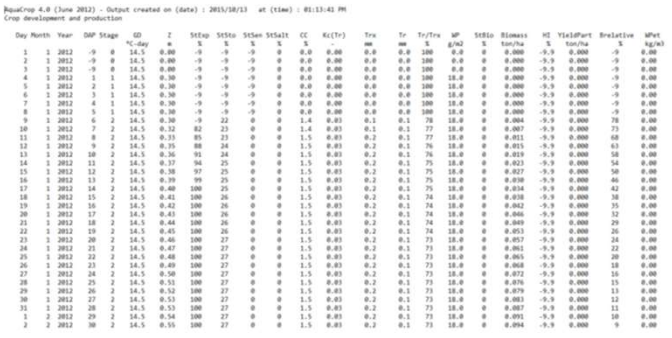
AquaCrop 4.0 (June 2012) - Output created on (date) : 2015/10/13 at (time) : 01:13:41 PM
Water content in soil profile (WCTotal layer: 0.00 - 1.20 m) and root zone (Wr with Zrx = 1.00 m)

Day	Month	Year	DAP	Stage	WCTot mm	Wr(Zx) mm	Z m	Wr mm	Wr(SAT) mm	Wr(FC) mm	Wr(exp) mm	Wr(sto) mm	Wr(sen) mm	Wr(PWP) mm
1	1	2012	-9	0	239.0	199.0	0.00	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9
2	1	2012	-9	0	238.2	198.2	0.00	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9
3	1	2012	-9	0	237.4	197.4	0.00	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9	-9.9
4	1	2012	1	1	236.7	196.7	0.30	56.7	150.0	90.0	75.0	60.9	39.0	30.0
5	1	2012	2	1	236.1	196.1	0.30	56.1	150.0	90.0	75.0	60.9	39.0	30.0
6	1	2012	3	1	235.5	195.5	0.30	55.5	150.0	90.0	75.0	60.9	39.0	30.0
7	1	2012	4	1	235.0	195.0	0.30	55.0	150.0	90.0	75.0	60.9	39.0	30.0
8	1	2012	5	1	234.5	194.5	0.30	54.5	150.0	90.0	75.0	60.9	39.0	30.0
9	1	2012	6	2	233.9	193.9	0.30	54.7	151.8	91.1	77.0	61.6	39.9	30.4
10	1	2012	7	2	233.4	193.4	0.32	57.1	159.3	95.6	80.8	64.7	41.9	31.9
11	1	2012	8	2	232.9	192.9	0.33	59.4	166.3	99.8	84.3	67.5	43.7	33.3
12	1	2012	9	2	232.5	192.5	0.35	61.6	172.8	103.7	87.7	70.2	45.5	34.6
13	1	2012	10	2	232.0	192.0	0.36	63.7	179.1	107.5	90.9	72.7	47.1	35.8
14	1	2012	11	2	231.6	191.6	0.37	65.7	185.2	111.1	93.9	75.2	48.7	37.0
15	1	2012	12	2	231.2	191.2	0.38	67.6	191.0	114.6	96.9	77.6	50.2	38.2
16	1	2012	13	2	230.8	190.8	0.39	69.5	196.6	117.9	99.7	79.8	51.7	39.3
17	1	2012	14	2	230.5	190.5	0.40	71.3	202.0	121.2	102.5	82.0	53.1	40.4
18	1	2012	15	2	230.1	190.1	0.41	73.1	207.3	124.4	105.2	84.2	54.5	41.5
19	1	2012	16	2	229.8	189.8	0.42	74.8	212.5	127.5	107.8	86.3	55.9	42.5
20	1	2012	17	2	229.5	189.5	0.43	76.5	217.5	130.5	110.3	88.3	57.2	43.5
21	1	2012	18	2	229.2	189.2	0.44	78.1	222.4	133.4	112.8	90.3	58.5	44.5
22	1	2012	19	2	228.8	188.8	0.45	79.7	227.2	136.3	115.3	92.3	59.8	45.4
23	1	2012	20	2	228.5	188.5	0.46	81.3	232.0	139.2	117.6	94.2	61.0	46.4
24	1	2012	21	2	228.2	188.2	0.47	82.9	236.6	142.0	120.0	96.0	62.2	47.3
25	1	2012	22	2	228.0	188.0	0.48	84.4	241.2	144.7	122.3	97.9	63.4	48.2
26	1	2012	23	2	227.7	187.7	0.49	85.9	245.6	147.4	124.5	99.7	64.6	49.1
27	1	2012	24	2	227.4	187.4	0.50	87.4	250.0	150.0	126.8	101.5	65.7	50.0
28	1	2012	25	2	227.1	187.1	0.51	88.9	254.4	152.6	128.9	103.2	66.9	50.9
29	1	2012	26	2	226.8	186.8	0.52	90.3	258.7	155.2	131.1	104.9	68.0	51.7
30	1	2012	27	2	226.6	186.6	0.53	91.7	262.9	157.7	133.2	106.6	69.1	52.6
31	1	2012	28	2	226.3	186.3	0.53	93.1	267.1	160.2	135.3	108.3	70.2	53.4
1	2	2012	29	2	226.1	186.1	0.54	94.6	271.2	162.7	137.4	110.0	71.3	54.2



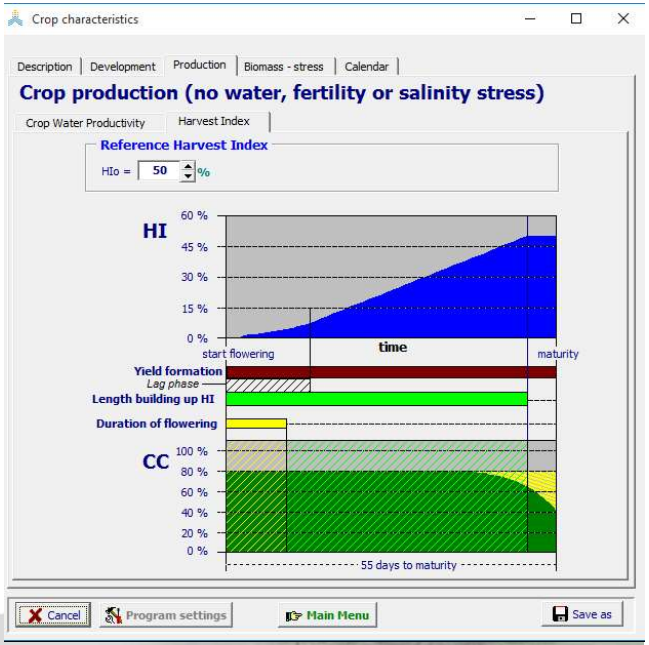
AquaCrop 4.0 (June 2012) - Output created on (date) : 2015/10/13 at (time) : 01:13:41 PM
Electrical conductivity of the saturated soil-paste extract (dS/m) at various depths (at center of compartments)

				at depth (m):	0.05	0.15	0.25	0.35	0.45	0.55	0.65	0.75
Day	Month	Year	DAP	Stage	ECe1	ECe2	ECe3	ECe4	ECe5	ECe6	ECe7	ECe8
1	1	2012	-9	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
2	1	2012	-9	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3	1	2012	-9	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
4	1	2012	1	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5	1	2012	2	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
6	1	2012	3	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	1	2012	4	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
8	1	2012	5	1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
9	1	2012	6	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
10	1	2012	7	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
11	1	2012	8	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
12	1	2012	9	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
13	1	2012	10	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
14	1	2012	11	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
15	1	2012	12	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
16	1	2012	13	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
17	1	2012	14	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
18	1	2012	15	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
19	1	2012	16	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
20	1	2012	17	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
21	1	2012	18	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
22	1	2012	19	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
23	1	2012	20	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
24	1	2012	21	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
25	1	2012	22	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
26	1	2012	23	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
27	1	2012	24	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
28	1	2012	25	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
29	1	2012	26	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
30	1	2012	27	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
31	1	2012	28	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
1	2	2012	29	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0



AquaCrop 4.0 (June 2012) - Output created on (date) : 2015/10/13 at (time) : 01:13:41 PM
Crop development and production

Day	Month	Year	DAP	Stage	GD °C.day	Z m	StExp %	StSto %	StSen %	StSalt %	CC %	Kc(Tr)	Trx mm	Tr mm	Tr/Trx %	WP g/m2	StBio %	Biomass ton/ha	HI %	YieldPart ton/ha	Brelative %	WPet kg/m3
1	1	2012	-9	0	14.5	0.00	-9	-9	-9	0	0.0	0.00	0.0	0.0	100	0.0	0	0.000	-9.9	0.000	-9	0.00
2	1	2012	-9	0	14.5	0.00	-9	-9	-9	0	0.0	0.00	0.0	0.0	100	0.0	0	0.000	-9.9	0.000	-9	0.00
3	1	2012	-9	0	14.5	0.00	-9	-9	-9	0	0.0	0.00	0.0	0.0	100	0.0	0	0.000	-9.9	0.000	-9	0.00
4	1	2012	1	1	14.5	0.30	-9	-9	-9	0	0.0	0.00	0.0	0.0	100	18.0	0	0.000	-9.9	0.000	-9	0.00
5	1	2012	2	1	14.5	0.30	-9	-9	-9	0	0.0	0.00	0.0	0.0	100	18.0	0	0.000	-9.9	0.000	-9	0.00
6	1	2012	3	1	14.5	0.30	-9	-9	-9	0	0.0	0.00	0.0	0.0	100	18.0	0	0.000	-9.9	0.000	-9	0.00
7	1	2012	4	1	14.5	0.30	-9	-9	-9	0	0.0	0.00	0.0	0.0	100	18.0	0	0.000	-9.9	0.000	-9	0.00
8	1	2012	5	1	14.5	0.30	-9	-9	-9	0	0.0	0.00	0.0	0.0	100	18.0	0	0.000	-9.9	0.000	-9	0.00
9	1	2012	6	2	14.5	0.30	-9	22	0	0	1.4	0.03	0.1	0.1	78	18.0	0	0.004	-9.9	0.000	78	0.00
10	1	2012	7	2	14.5	0.32	82	23	0	0	1.4	0.03	0.1	0.1	77	18.0	0	0.007	-9.9	0.000	73	0.00
11	1	2012	8	2	14.5	0.33	85	23	0	0	1.5	0.03	0.2	0.1	77	18.0	0	0.011	-9.9	0.000	68	0.00
12	1	2012	9	2	14.5	0.35	88	24	0	0	1.5	0.03	0.2	0.1	76	18.0	0	0.015	-9.9	0.000	63	0.00
13	1	2012	10	2	14.5	0.36	91	24	0	0	1.5	0.03	0.2	0.1	76	18.0	0	0.019	-9.9	0.000	58	0.00
14	1	2012	11	2	14.5	0.37	94	25	0	0	1.5	0.03	0.2	0.1	75	18.0	0	0.023	-9.9	0.000	54	0.00
15	1	2012	12	2	14.5	0.38	97	25	0	0	1.5	0.03	0.2	0.1	75	18.0	0	0.027	-9.9	0.000	50	0.00
16	1	2012	13	2	14.5	0.39	99	25	0	0	1.5	0.03	0.2	0.1	75	18.0	0	0.030	-9.9	0.000	46	0.00
17	1	2012	14	2	14.5	0.40	100	25	0	0	1.5	0.03	0.2	0.1	75	18.0	0	0.034	-9.9	0.000	42	0.00
18	1	2012	15	2	14.5	0.41	100	26	0	0	1.5	0.03	0.2	0.1	74	18.0	0	0.038	-9.9	0.000	38	0.00
19	1	2012	16	2	14.5	0.42	100	26	0	0	1.5	0.03	0.2	0.1	74	18.0	0	0.042	-9.9	0.000	35	0.00
20	1	2012	17	2	14.5	0.43	100	26	0	0	1.5	0.03	0.2	0.1	74	18.0	0	0.046	-9.9	0.000	32	0.00
21	1	2012	18	2	14.5	0.44	100	26	0	0	1.5	0.03	0.2	0.1	74	18.0	0	0.049	-9.9	0.000	29	0.00
22	1	2012	19	2	14.5	0.45	100	26	0	0	1.5	0.03	0.2	0.1	74	18.0	0	0.053	-9.9	0.000	26	0.00
23	1	2012	20	2	14.5	0.46	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.057	-9.9	0.000	24	0.00
24	1	2012	21	2	14.5	0.47	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.061	-9.9	0.000	22	0.00
25	1	2012	22	2	14.5	0.48	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.065	-9.9	0.000	20	0.00
26	1	2012	23	2	14.5	0.49	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.068	-9.9	0.000	18	0.00
27	1	2012	24	2	14.5	0.50	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.072	-9.9	0.000	16	0.00
28	1	2012	25	2	14.5	0.51	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.076	-9.9	0.000	15	0.00
29	1	2012	26	2	14.5	0.52	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.079	-9.9	0.000	13	0.00
30	1	2012	27	2	14.5	0.53	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.083	-9.9	0.000	12	0.00
31	1	2012	28	2	14.5	0.53	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.087	-9.9	0.000	11	0.00
1	2	2012	29	2	14.5	0.54	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.091	-9.9	0.000	10	0.00
2	2	2012	30	2	14.5	0.55	100	27	0	0	1.5	0.03	0.2	0.1	73	18.0	0	0.094	-9.9	0.000	9	0.00



Yield Part : Yield (HI x Biomass)

Biomass : Cumulative biomass produced

DAP : Days after planting
Stage : 0: before/after planting
Stage : 1: emergence or transplant recovery
Stage : 2: vegetative stage
Stage : 3: flowering
Stage : 4: yield formation and ripening
GD : Growing degrees
Z : Effective rooting depth
StExp : Percent water stress reducing leaf expansion
StSto : Percent water stress inducing stomatal closure
StSen : Percent water stress triggering early canopy senescence
StSalt : Percent salinity stress
CC : Green Canopy Cover
Kc(Tr) : Crop coefficient for transpiration
Trx : Maximum crop transpiration
Tr : Crop transpiration
Tr/Trx : Relative crop transpiration (100 Tr/Trx)
WP : Crop water productivity adjusted for CO2, soil fertility and products synthesized
StBio : Percent temperature stress affecting biomass production
Biomass : Cumulative biomass produced
HI : Harvest Index adjusted for failure of pollination, inadequate photosynthesis and water stress
Yield Part : Yield (HI x Biomass)
Brelative : Relative biomass (Reference: no water, no soil fertility, no soil salinity stress)
WPet : ET Water productivity for yield part (kg yield produced per m3 water evapotranspired)

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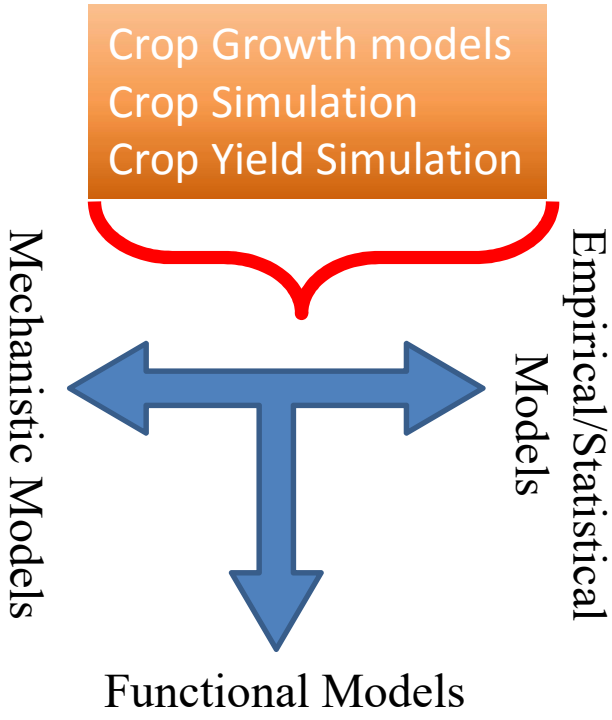

Crop Growth/Production

- → Weather Conditions
- → Soil Conditions
- → Crop Management
- → Biotic Factors
- → Stress

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Empirical/Statistical Models

Empirical models are simply a regression analysis between factor(s) that affect the plant growth and crop yield

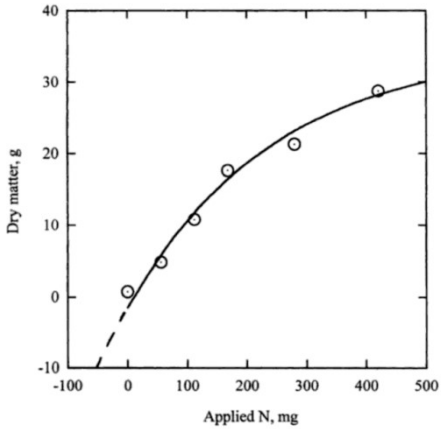
- Linear Regression
- Growth Indices
- Principal Component
- Markov Chain

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \ldots\ldots + e$$

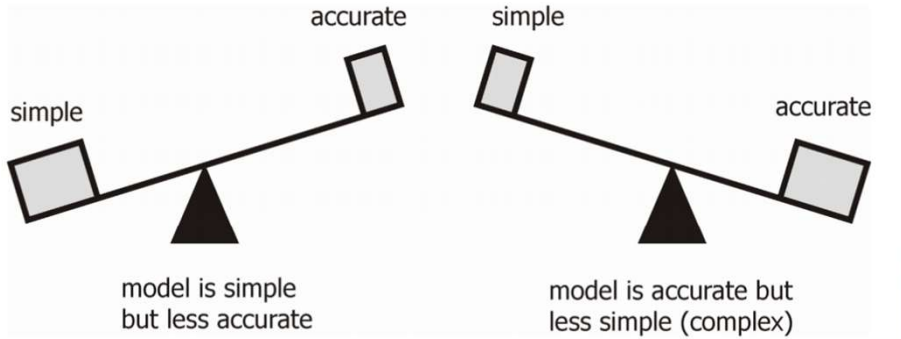
$$Y = \beta_0 + \Sigma\, \beta_i G_i + e \quad \Leftarrow \quad G_i = \sum_{w=n_1}^{n_2} r_{iw}\, X_{iw}$$

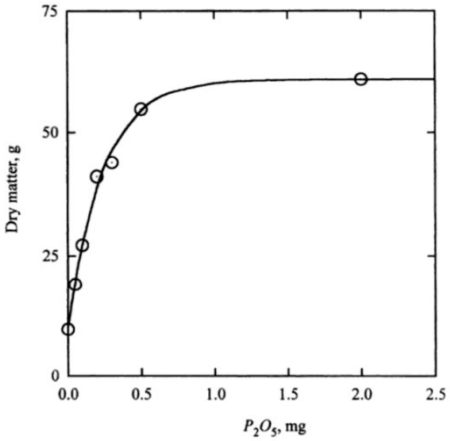
$$Y = Y_0 + (Y_m - Y_0)[1 - \exp(-cN)]$$

$$Y_m - Y = (Y_m - Y_0)\exp(-cN)$$



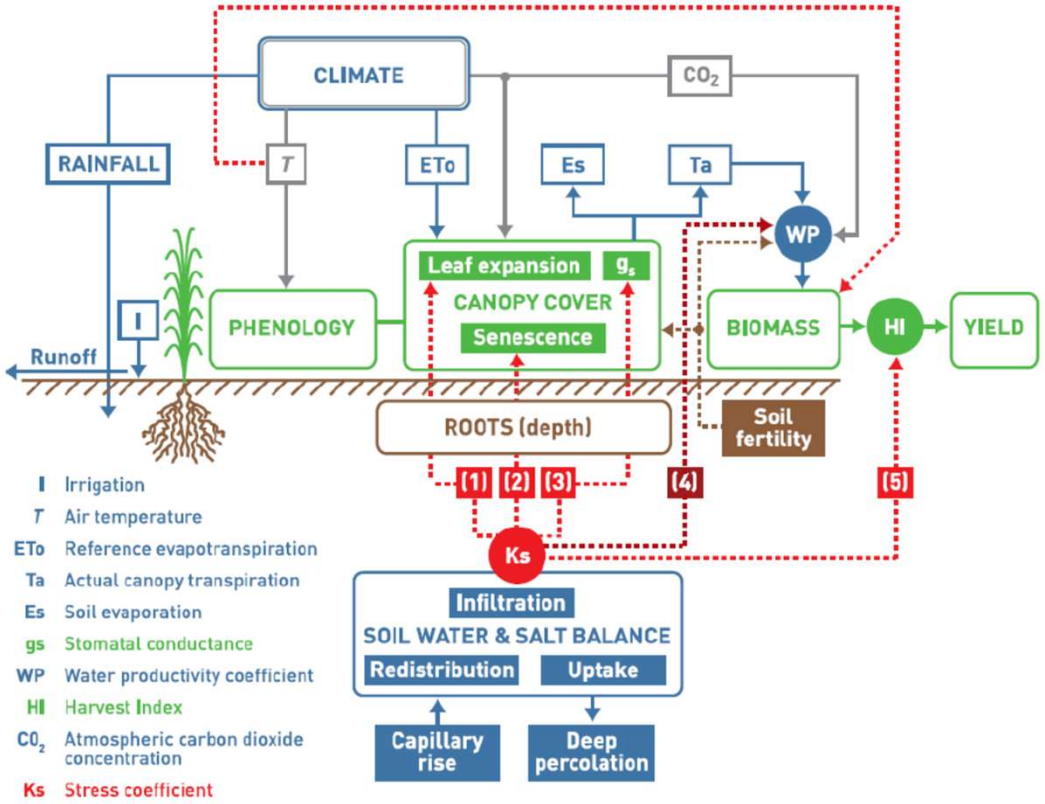
$$Y = 9.6 + 51.4[1 - \exp(-4.16P_2O_5)]$$

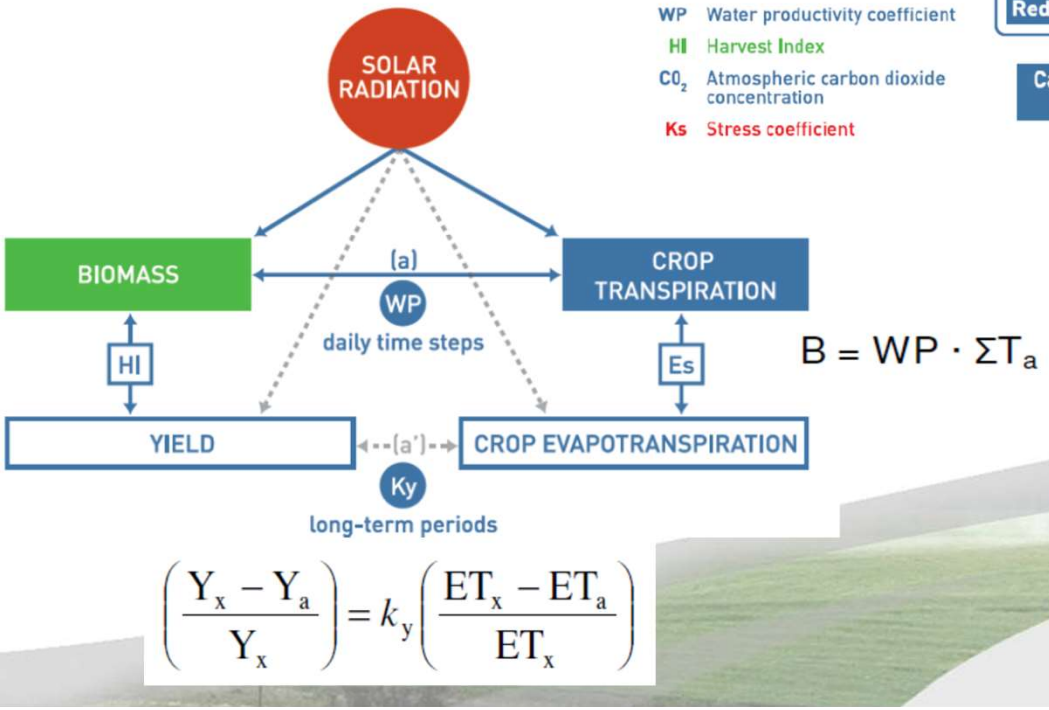




Mechanistic Models

Mechanistic models are simulating the fundamental mechanisms governing the crop growth and yield





$$B = WP \cdot \Sigma T_a$$

$$\left(\frac{Y_x - Y_a}{Y_x}\right) = k_y \left(\frac{ET_x - ET_a}{ET_x}\right)$$

Functional Models

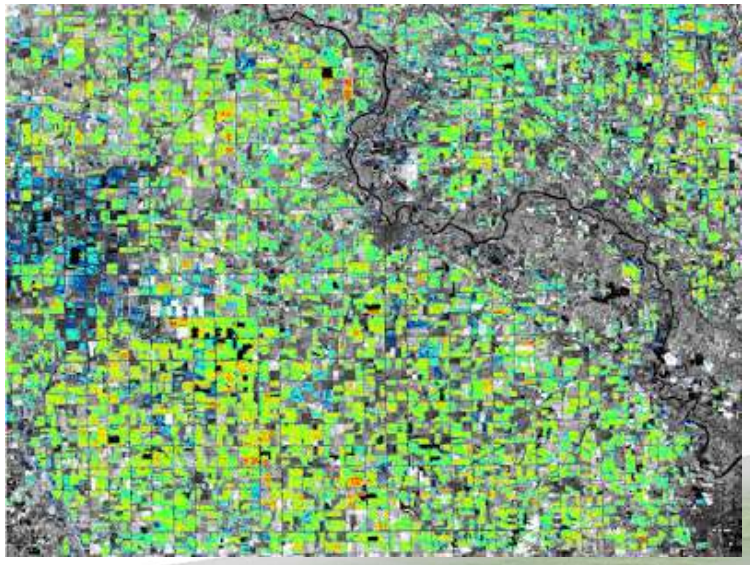
Functional models are simulating crop growth using graphical interpretation of the fundamental processes (System Dynamics)

Earth observation potential in crop yield estimation?

Several satellites has a capability to measure the land reflectance at spectral range that can be used for plant monitoring

Major ranges for plant monitoring are “Red” and “Infrared”

However, the ranges in the shortwave infrared and Thermal inferred (TIR) are also valuable for developing several plant growth indicators related to moisture content in plant and soil.



Scalable Satellite-based Crop Yield Mapper

Based on statistical relationship between NDVI and ground data at 29,000 samples.
Model run under Google’s Earth Engine

(Lobell et al., 2015)

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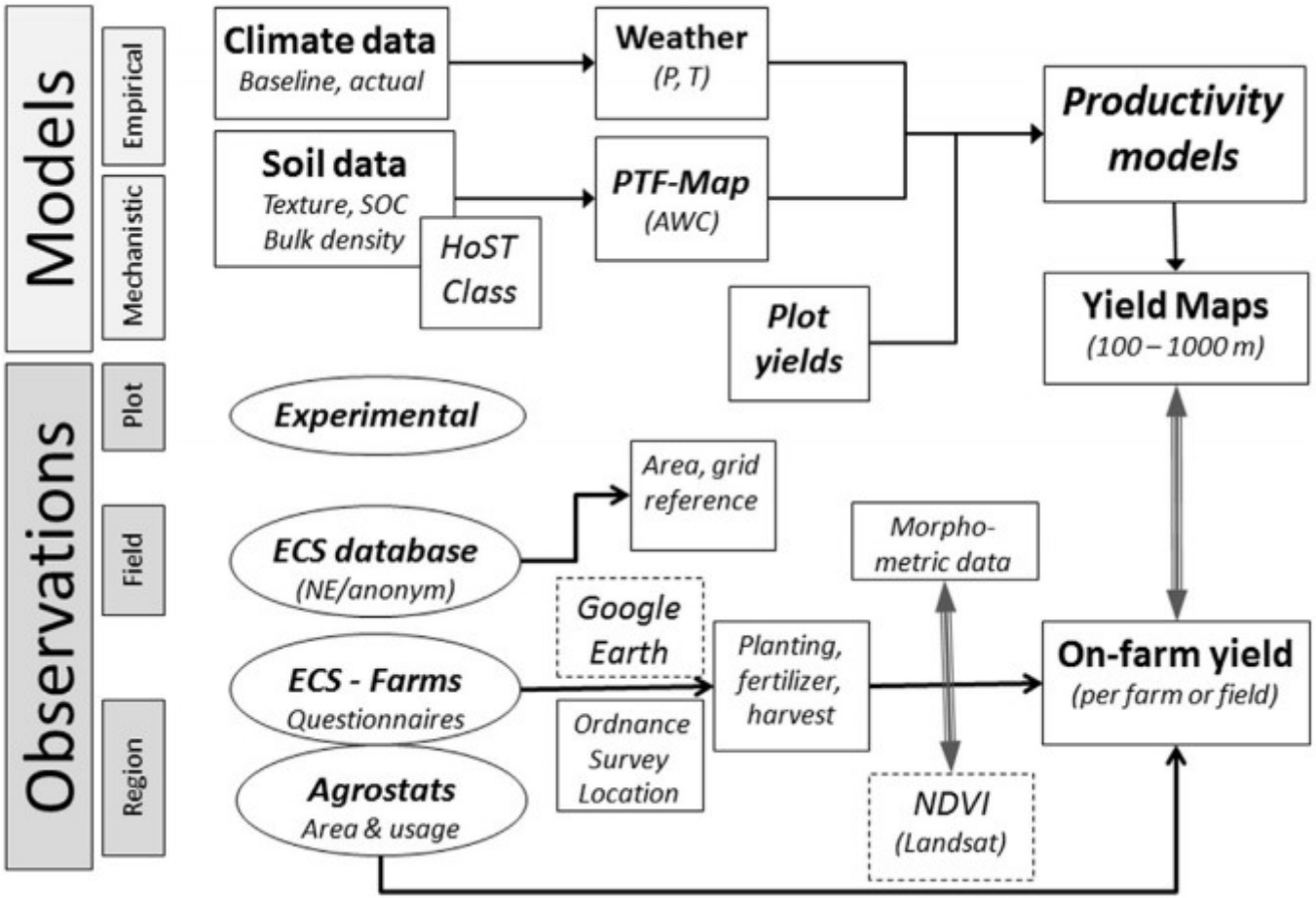

(Richter et al., 2016)

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Basic parameters that has impact on crop growth and can be monitored by satellite are including:

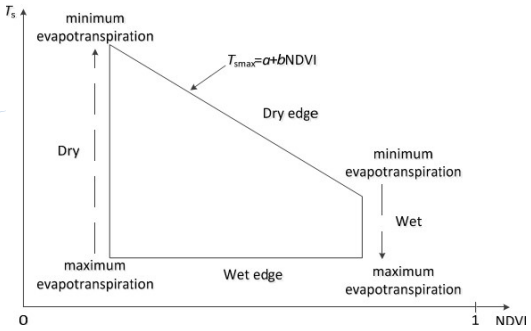
Growth:

→ Biomass production
→ Leaf area
→ Vegetation indices and chlorophyll content

Indices*	Formulae*	References
NDVI	$\frac{NIR-Red}{NIR+Red}$	Rouse et al. (1974)
EVI	$G\frac{NIR-Red}{NIR+C_1Red-C_2Blue+L}(1+L)$	Huete (1988)
Mid-infrared index	$\frac{MIR}{SWIR}$	Musick and Pelletier (1988)
MSI	$\frac{MIR}{NIR}$	Rock et al. (1986)
NDVI green	$\frac{NIR-Green}{NIR+Green}$	Gitelson et al. (1996)
NDWI	$\frac{NIR-SWIR}{NIR+SWIR}$	Gao (1996)
RSR	$\frac{NIR}{Red}\left(1-\frac{SWIR-SWIR_{min}}{SWIR_{max}-SWIR_{min}}\right)$	Brown et al. (2000), Chen et al. (2002)
SR	$\frac{NIR}{Red}$	Birth and McVey (1968), Chen et al. (2002)
TVI	$\left(\frac{NIR-Red}{NIR+Red}+0.5\right)^{1/2}\times 100$	Nellis and Briggs (1992)

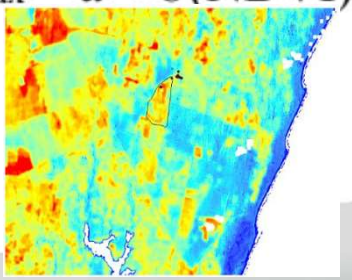
Water:

→Evapotranspiration
→Water deficiency (Dryness index)
→ Water Use Efficiency



$$TVDI = (T_s - T_{smin})/(T_{smax} - T_{smin})$$

$$T_{smax} = a + b(NDVI)$$



Nutrients:

→ Leaf N (kg/ha)

$$NDNI = \frac{\log\left(\frac{1}{\rho_{1510}}\right) - \log\left(\frac{1}{\rho_{1680}}\right)}{\log\left(\frac{1}{\rho_{1510}}\right) + \log\left(\frac{1}{\rho_{1680}}\right)}$$

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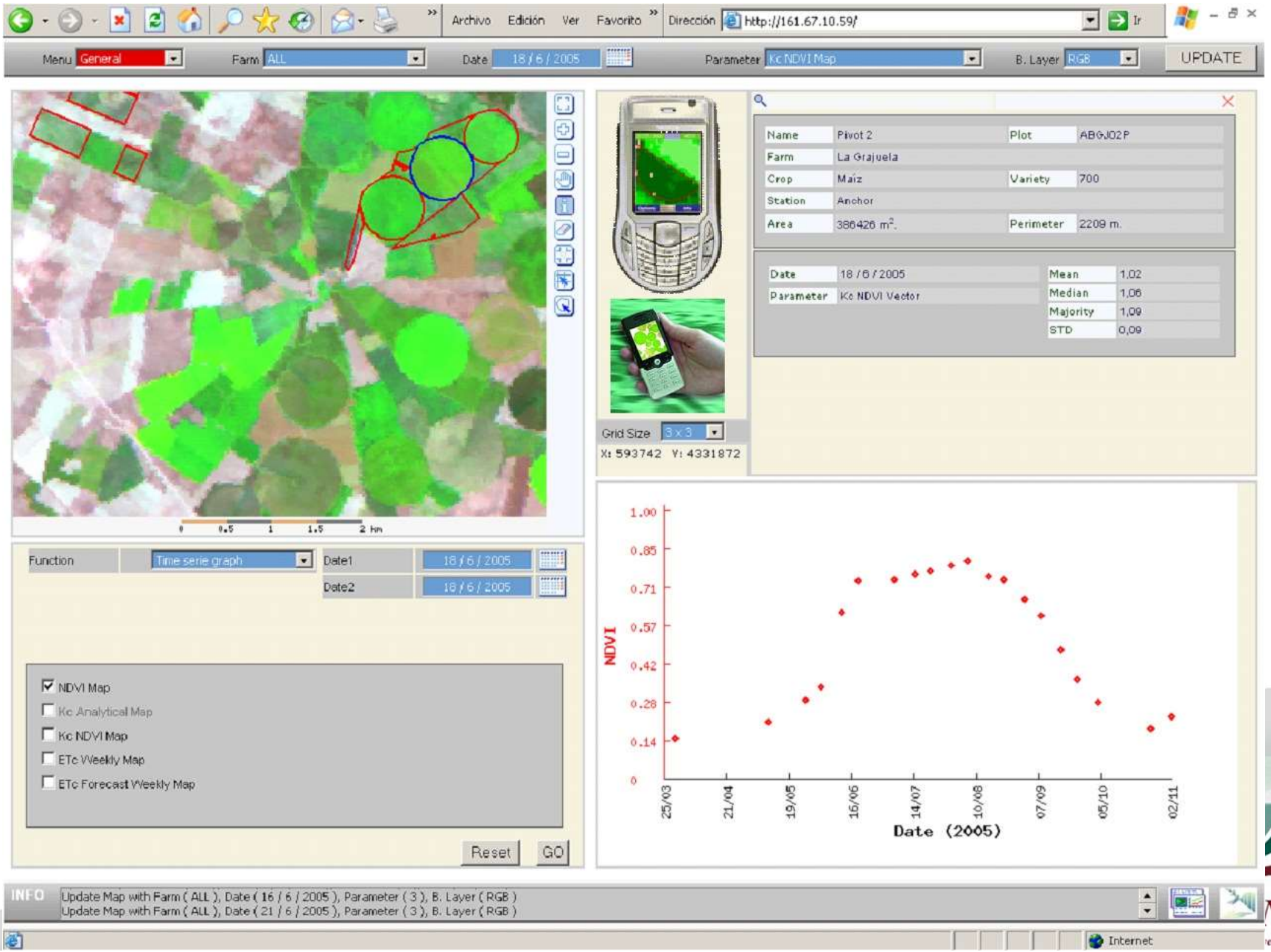
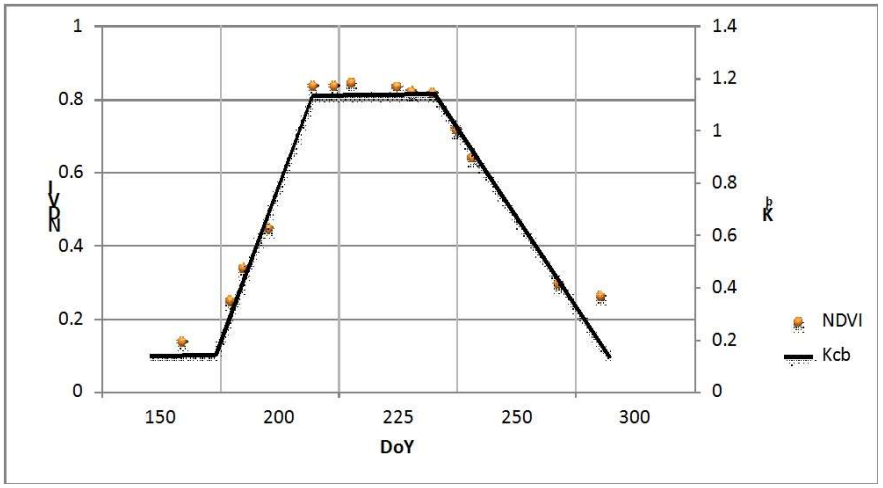
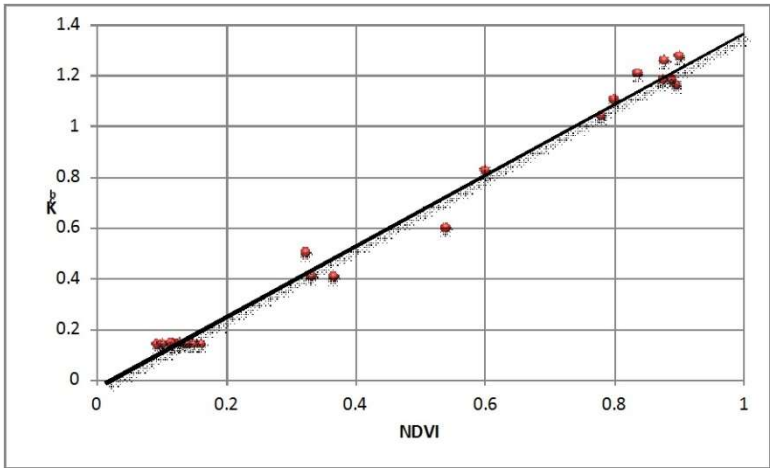
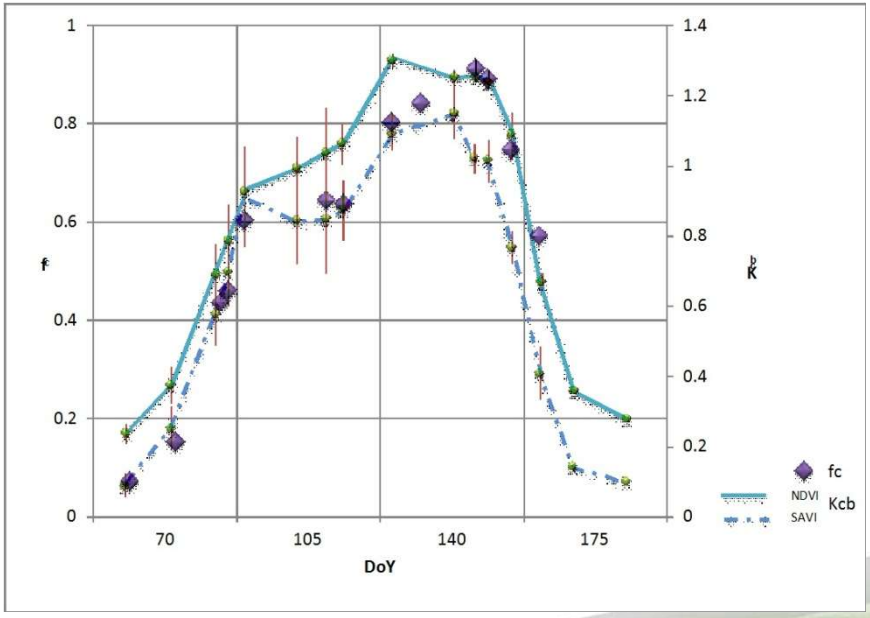
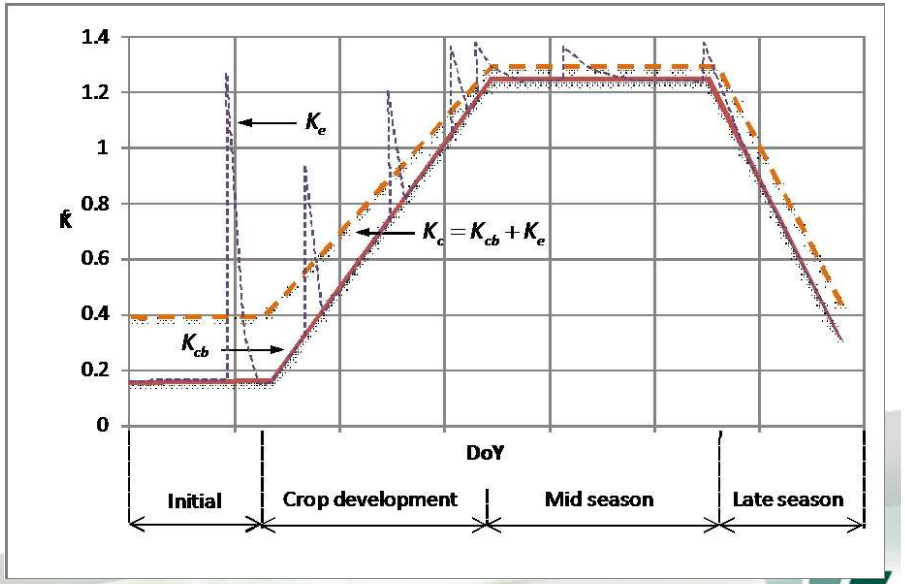
(Rocha et al., 2012)











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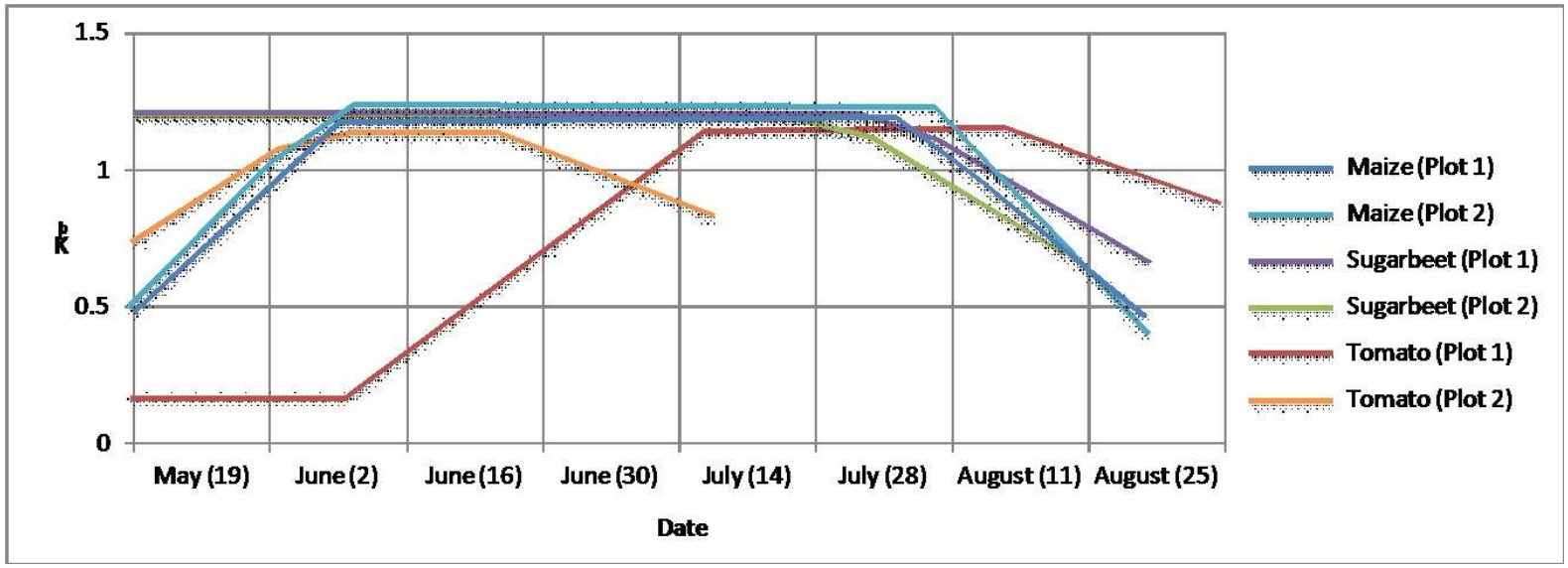

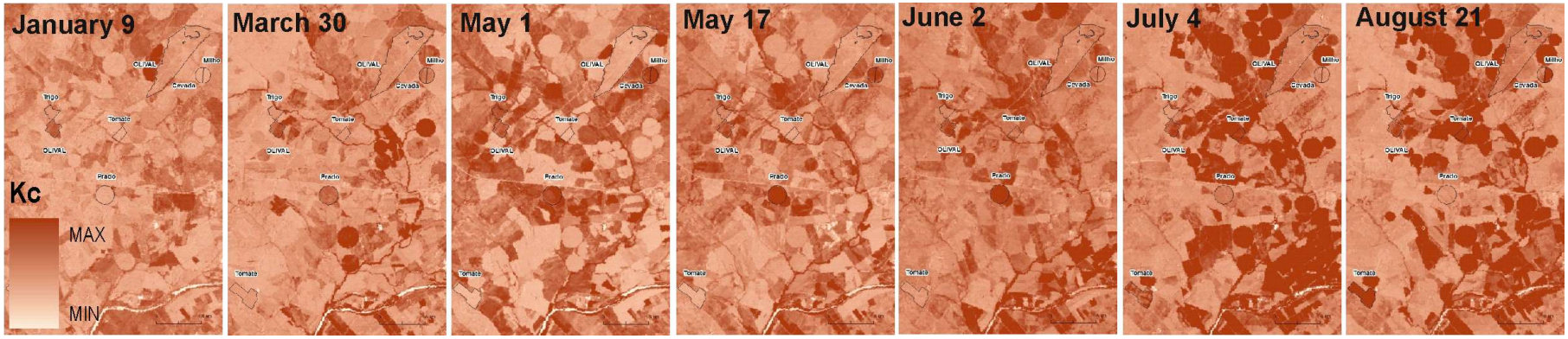

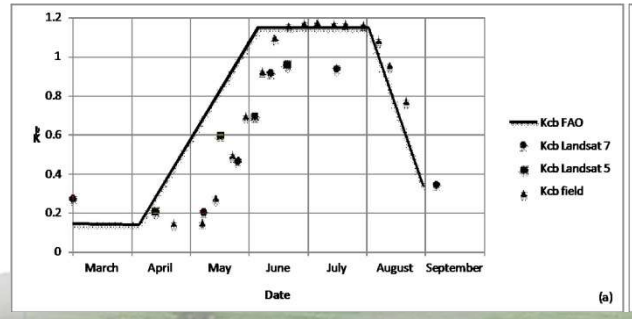

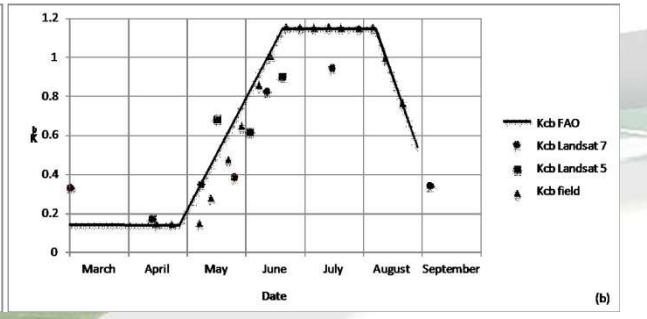

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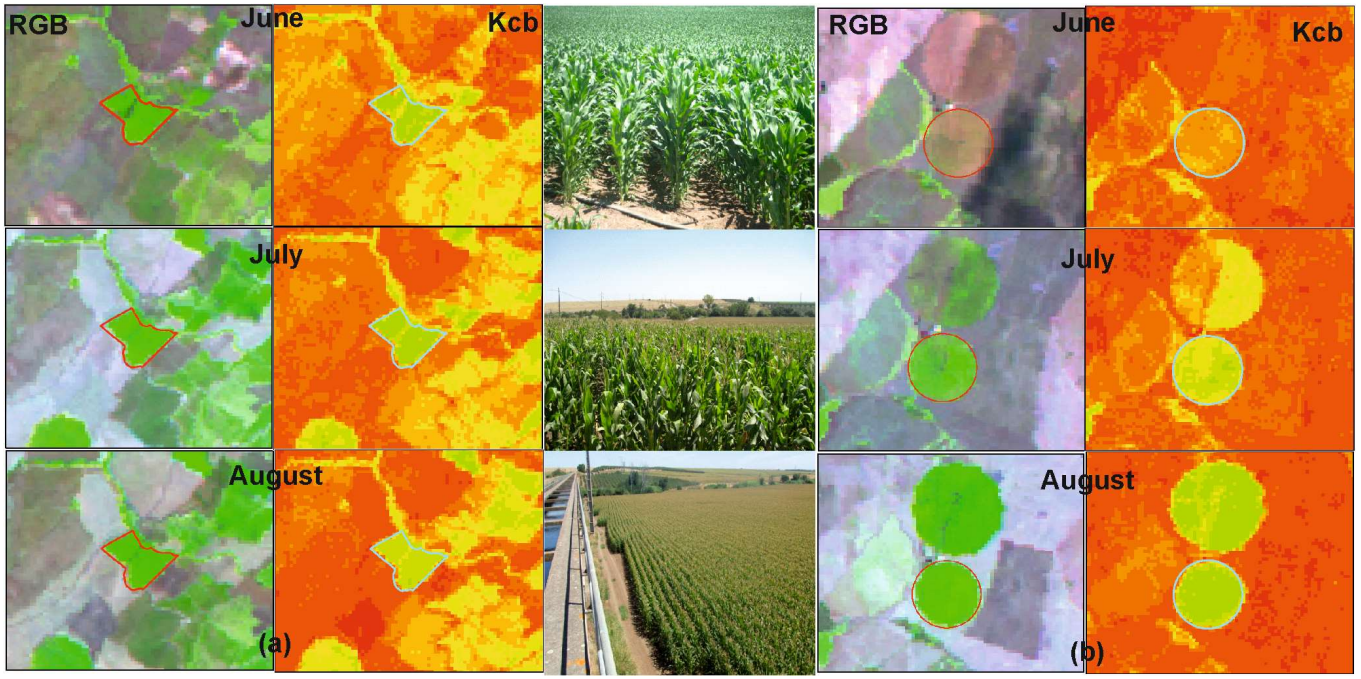

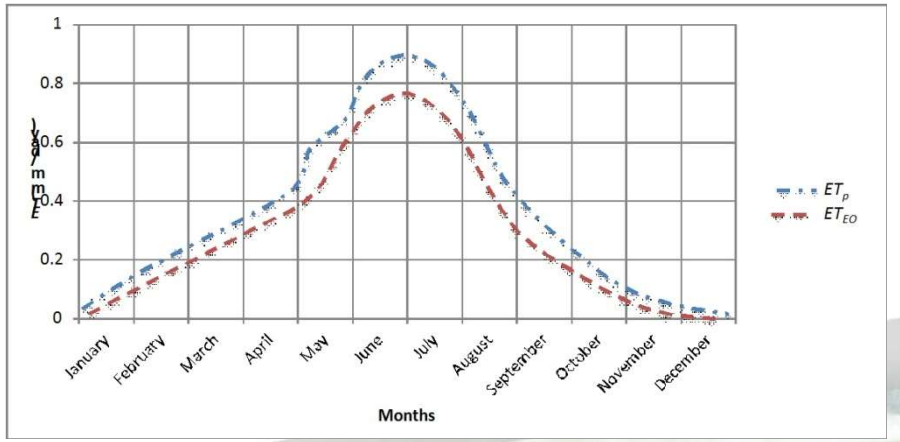

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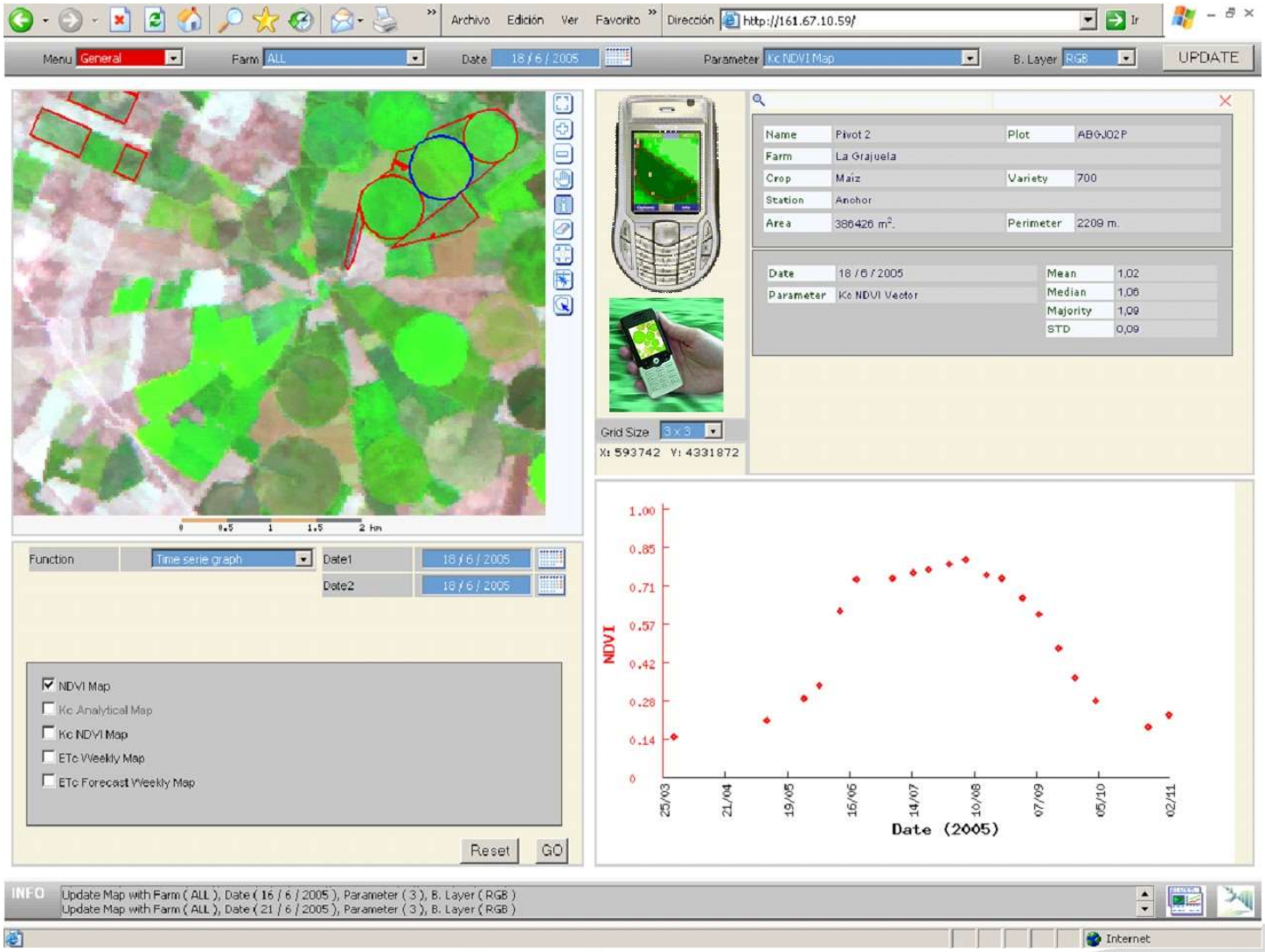

PLEIADES

(Participatory multi-Level EO-assisted tools for Irrigation water management and Agricultural Decision-Support)

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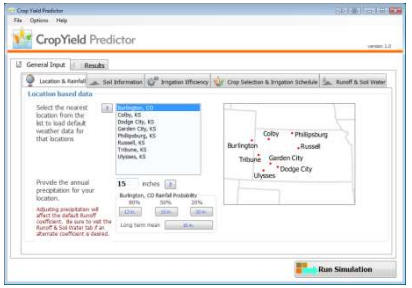

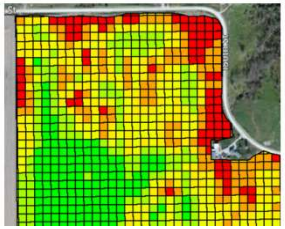

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Yield Monitoring

Ag Leader provides the most widely used grain yield monitoring technology in the world. Create and view yield and moisture maps while harvesting and instantly observe how field conditions affect yield. Make year-round management decisions based on this valuable information.

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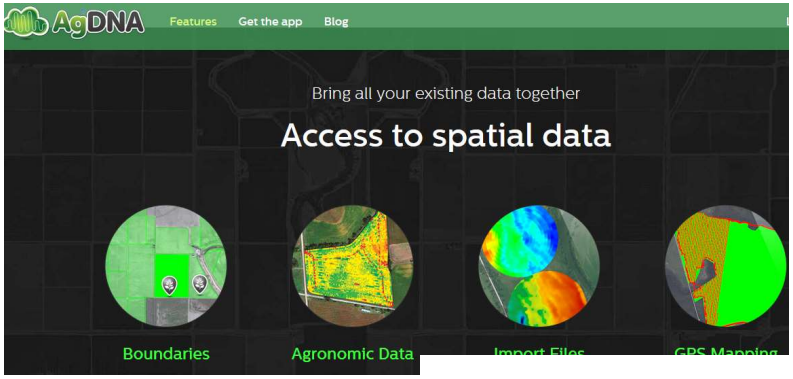

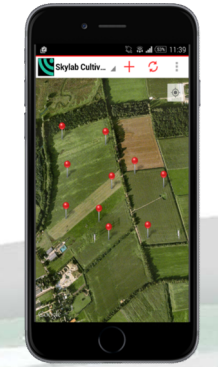

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