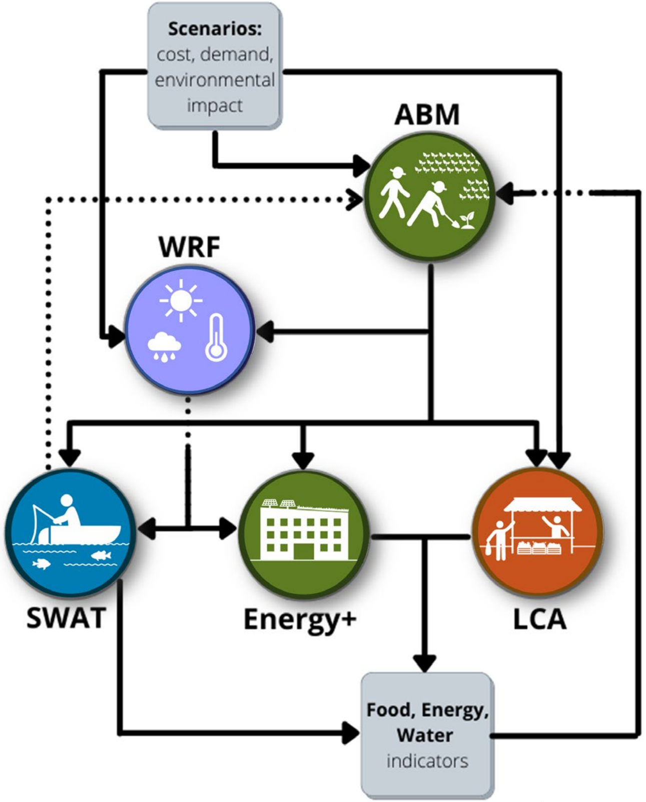
Growing fruits and vegetables in Iowa: an experiment to validate SWAT plant growth parameters

Authors: Tássia Mattos Brighenti, Natalja Čerkasova, Tiffanie F. Stone, Philip W. Gassman, Jeffrey G. Arnold, James R. Kiniry, Janette R. Thompson, Matt Liebman, Manyowa Meki, Raghavan Srinivasan, Ajay Nair, Michael J. White

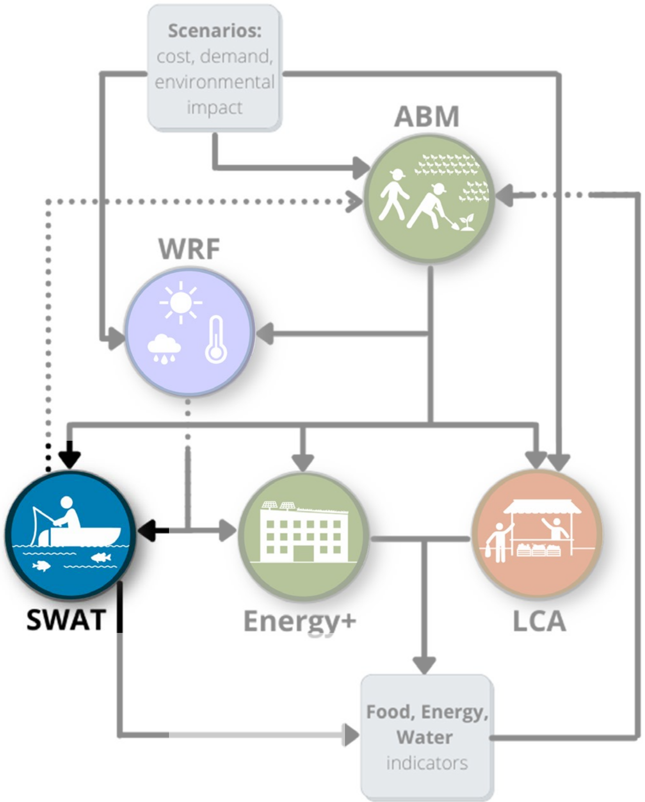
Iowa Urban FEWS – OVERVIEW

The project is focused on **developing sustainable food production systems** in the Des Moines–West Des Moines, IA Metropolitan Statistical Area (DMMSA). Multiple models are being integrated (co-simulation approach) to evaluate the impact of **converting cropland, peri-urban and/or urban landscapes to table food production**, in DMMSA transboundary and urban subareas.



SWAT model within the Iowa **UrbanFEWS**:

- **Quantify crop growth**.
- Hydrological cycling.
- Nutrient and sediment cycling and transport for cropping systems and associated management practices.
- Simulate future climate and land use change scenarios and characterize streamflow, nutrient, sediment load conditions, and yields production.



- **Why**? The needed to address food insecurity and environmental impacts is still a challenge in the 21st century.

- **How**? Ecohydrological models are a key tool for accurate system representation and impact measurement.

Modeling tools can assist with identifying the best **planting times and cultivation methods for each particular region and can evaluate the impact of food production on water and soil resources**. Therefore, there has been an increasing interest in pursuing research focused on developing sustainable food production systems.

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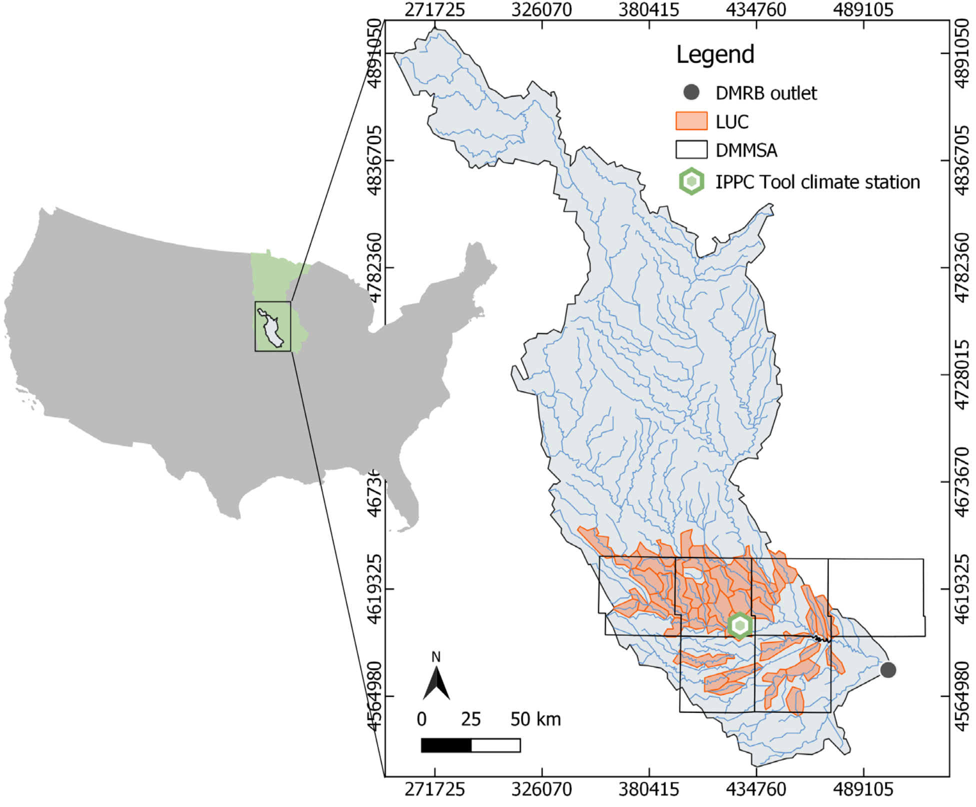
The objective of this study was to **validate crop growth parameters** for 24* fruit/vegetable crop types in the SWAT model.

(*) apple, blueberries, broccoli, cabbage, carrots, cherries, collard greens, cucumber, dry beans, grapes, lettuce, kale, melon, onion, pears, potato, pumpkin, raspberries, spinach, squash, strawberries, sweet corn, sweet potato, and tomato.

STUDY AREA

Des Moines River Basin (DMRB) 31,892 km^2

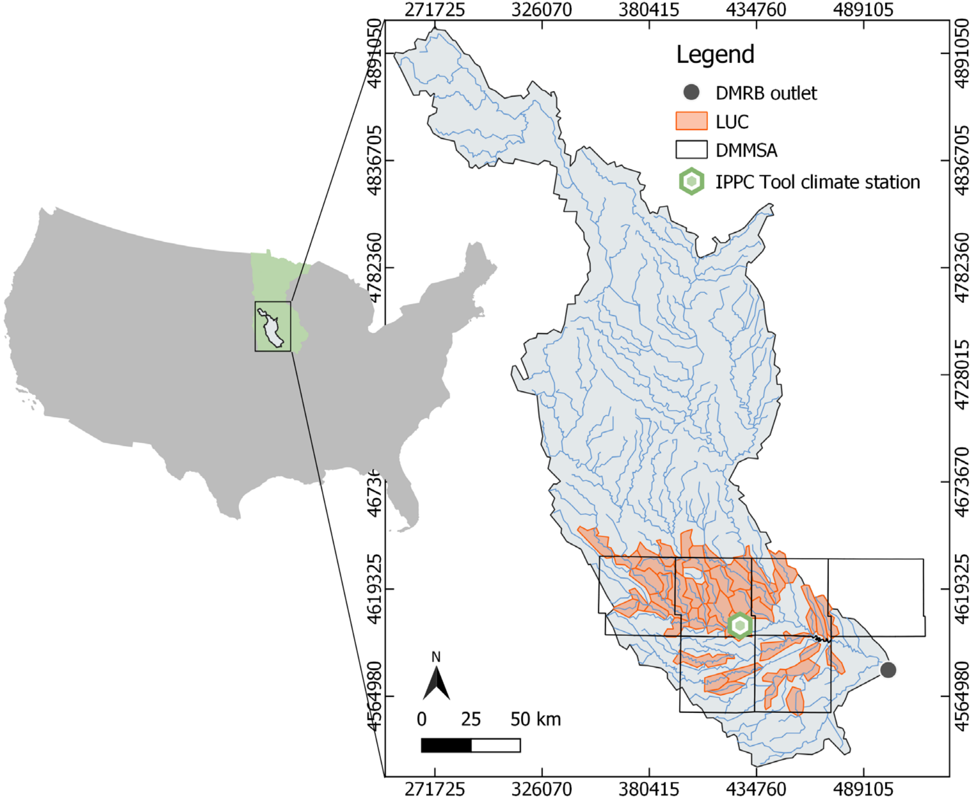
- **Land use**: soybean and corn fields representing together 70%.
- **Soil type**: Loamy Wisconsin Glacial Till (tile drainage represent 54%).
- **Precipitation and evapotranspiration**: 873 mm and 670 mm (annual average 1985-2018).

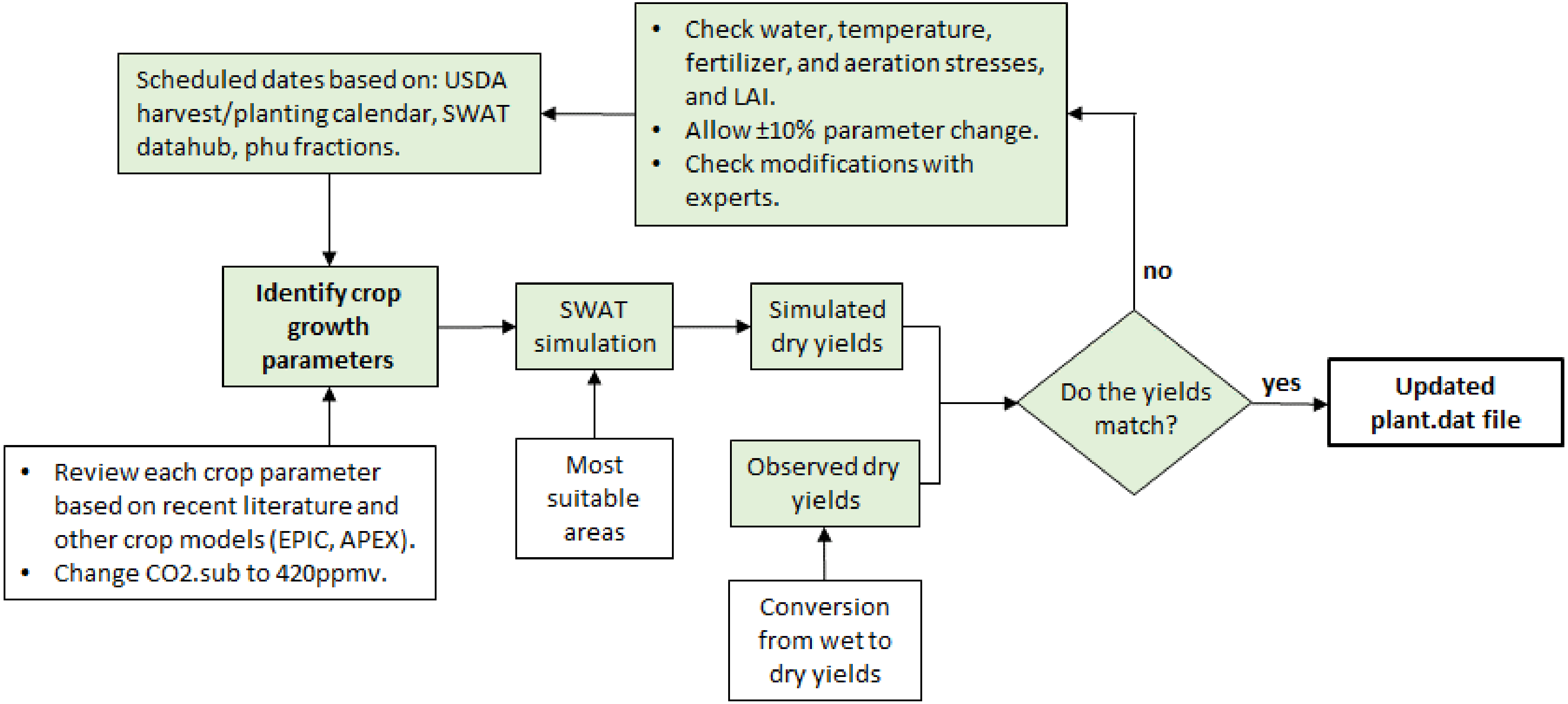


STUDY AREA

The Des Moines Metropolitan Statistical Area (DMMSA), which is the largest urban area in Iowa, served as approximate boundaries for choosing the areas to be replaced by fruits and vegetables due to:

- The focus of the Iowa UrbanFEWS project.
- Available data indicating **areas suitable for growing fruits and vegetables**.





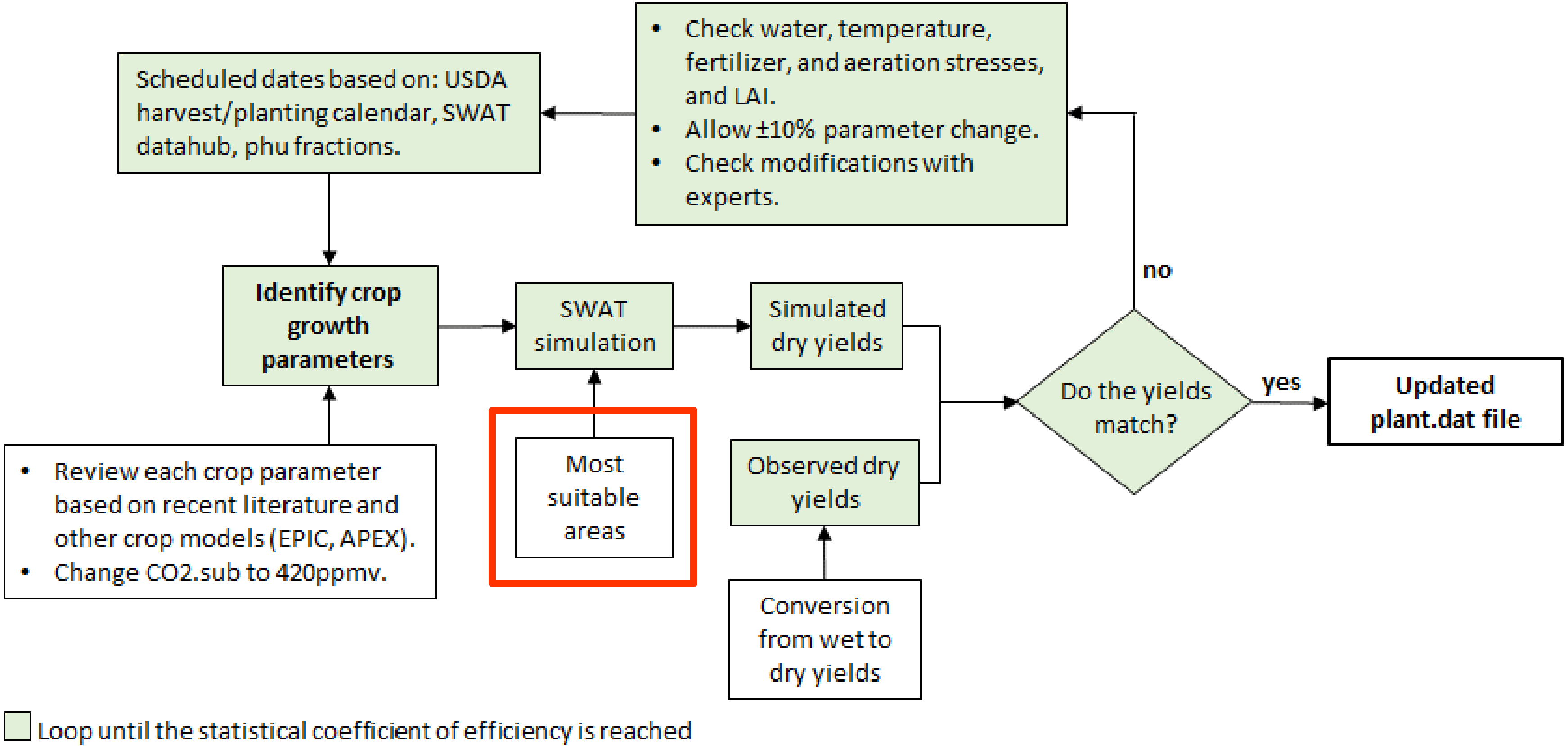
Loop until the statistical coefficient of efficiency is reached

Observed yields

Average yield values for fruit and vegetable production in the state of Iowa are not collected by the United States Agricultural Census.

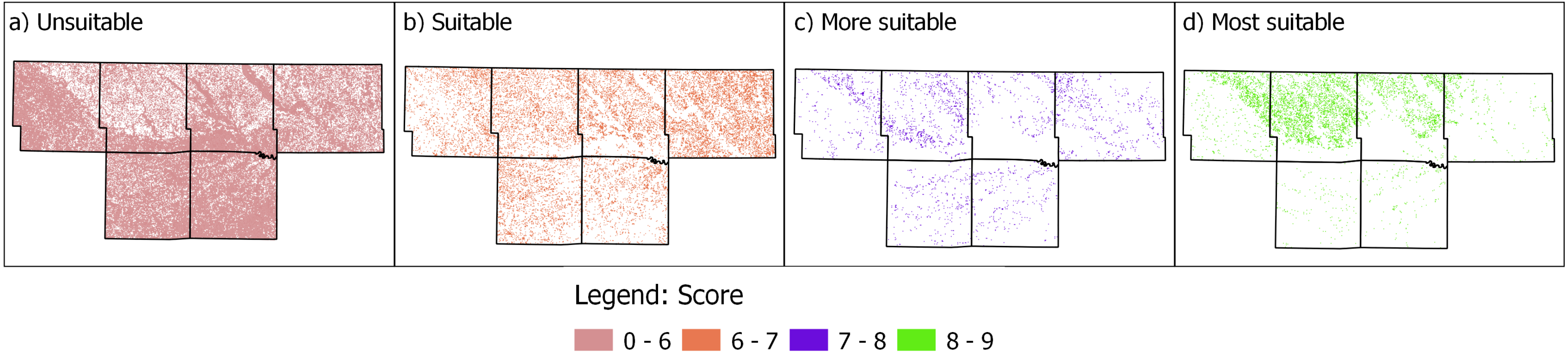
- National-scale FoodPrint Model that compiled average yields (2000 to 2010) from the United States Agricultural Census.
- Available Midwest yield values in combination with expert opinion.
- Fruit yields: national average yields were adjusted for Iowa production based on state Farm Service Agency (FSA) estimates in combination with input from two fruit crop specialists.

Crop type	Iowa average yields (ton/ha)	Crop type	Iowa average yields (ton/ha)
Apple	30.5	Lettuce	40.15
Blueberries	6.1	Melon	29.9
Broccoli	17.4	Onions	59.7
Cabbage	62.7	Pears	35.2
Carrots	62.7	Potatoes	45.2
Cherries	8.8	Pumpkin	35.9
Collard Greens	14.8	Raspberries	7.2
Sweet Corn	19.0	Spinach	18.8
Cucumber	20.1	Squash	21.9
Dry beans	2.0	Strawberries	58.7
Grapes	17.7	Sweet Potatoes	24.8
Kale	30.9	Tomatoes	90.3


Scheduled dates based on: USDA harvest/planting calendar, SWAT datahub, phu fractions.
• Check water, temperature, fertilizer, and aeration stresses, and LAI.
• Allow ±10% parameter change.
• Check modifications with experts.
Identify crop growth parameters
SWAT simulation
Simulated dry yields
no
Do the yields match?
yes
Updated plant.dat file
• Review each crop parameter based on recent literature and other crop models (EPIC, APEX).
• Change CO2.sub to 420ppmv.
Most suitable areas
Observed dry yields
Conversion from wet to dry yields
Loop until the statistical coefficient of efficiency is reached

Suitable Areas

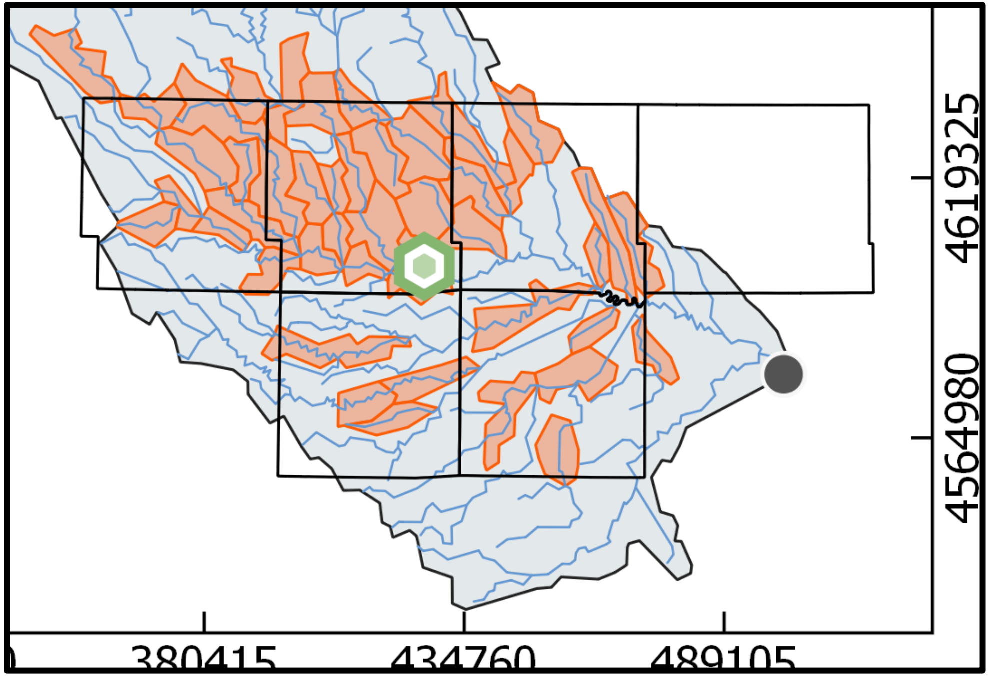
Suitable soil classes for fruits and vegetable production based on a scoring system (0 to 9) of the biophysical features:

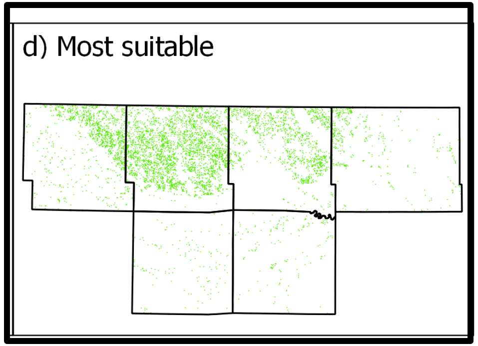


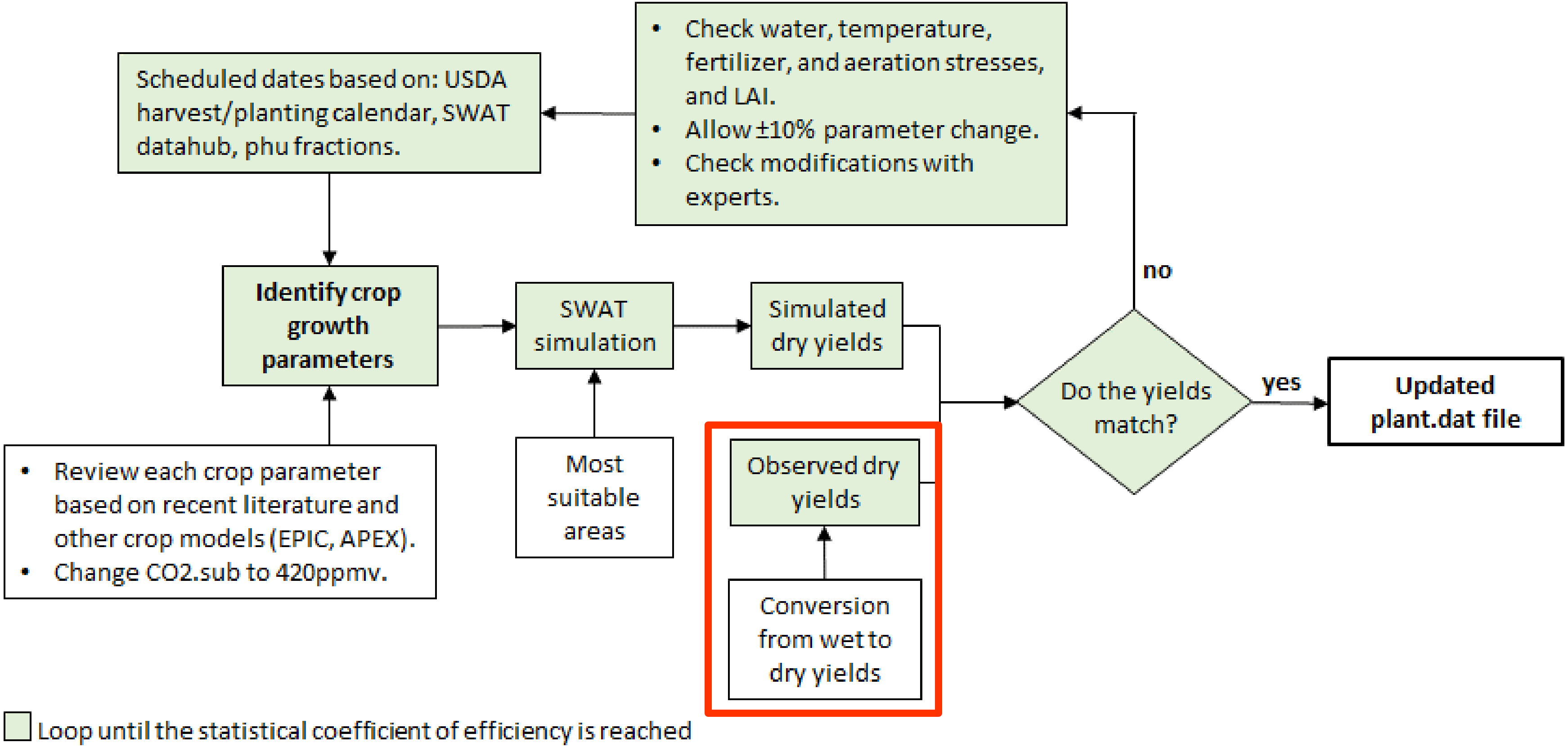
Five criteria with equal weighting:

1) zoned agricultural, 2) no flooding, 3) well-drained soil drainage class, 4) slope of 0 – 5% and 5) soil texture of sandy loam, loam or silt loam.

Suitable soil classes for fruits and vegetable production based on a scoring system of the biophysical features and the distribution between subbasins.







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Observed fresh to dry yields

Amount of water content of the crop types selected and the conversion from fresh to dry yields, to allow SWAT output comparison.

Crop variety	Water content (%)	Crop variety	Water content (%)
Apple	83	Lettuce	94
Blueberries	80	Melon	90
Broccoli	91	Onions	91
Cabbage	93	Pears	83
Carrots	88	Potatoes	79
Cherries	20	Pumpkin	92
Collard Greens	94	Raspberries	85
Sweet Corn	76	Spinach	92
Cucumber	96	Squash	91
Dry beans	0	Strawberries	92
Grapes	78	Sweet Potatoes	76
Kale	85	Tomatoes	94

The SWAT plant growth

Plant growth formulation is based on **daily accumulation of heat units**.

Plant development is dependent on temperature, water, nitrogen or phosphorus stress; operation management timing; the leaf area development; light interception; and conversion of intercepted light into biomass assuming a plant species-specific radiation-use efficiency.

The plant growth database contains 36 parameters:

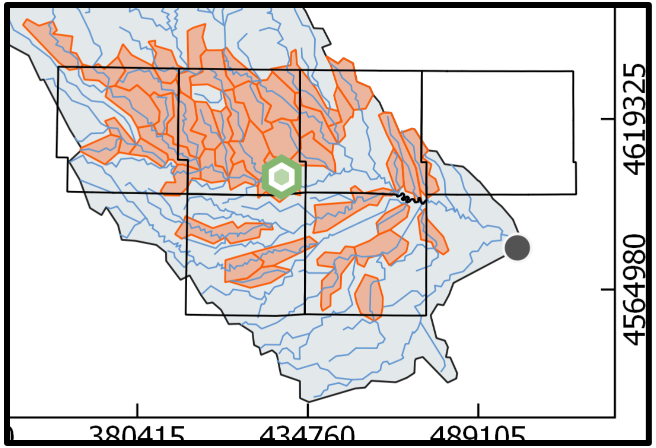
Parameter SWAT code	Parameter description
IDC	Land cover/plant classification
BIO_E	Radiation use efficiency
HVSTI	Harvest index
BLAI	Max Potential Leaf Area Index
FRGRW1	PHU fraction point 1
LAIMX1	BLAI fraction point 1
FRGRW2	PHU fraction point 2
LAIMX2	BLAI fraction point 2
DLAI	Growing season decline fraction

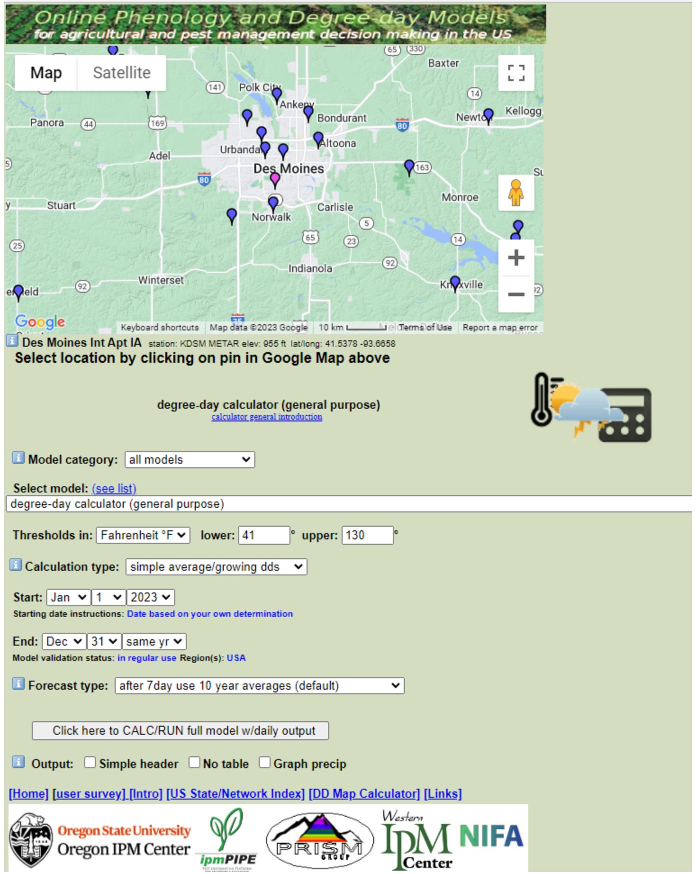
Parameter SWAT code	Parameter description
CHTMX	Maximum canopy height
RDMX	Maximum root depth
T_OPT	Optimal growth temperature
T_BASE	Minimum growth temperature
CNYLD	Nitrogen in yield
CPYLD	Phosphorus in yield
PLTNFR(1)	Nitrogen uptake emergence
PLTNFR(2)	Nitrogen uptake midseason
PLTNFR(3)	Nitrogen uptake maturity

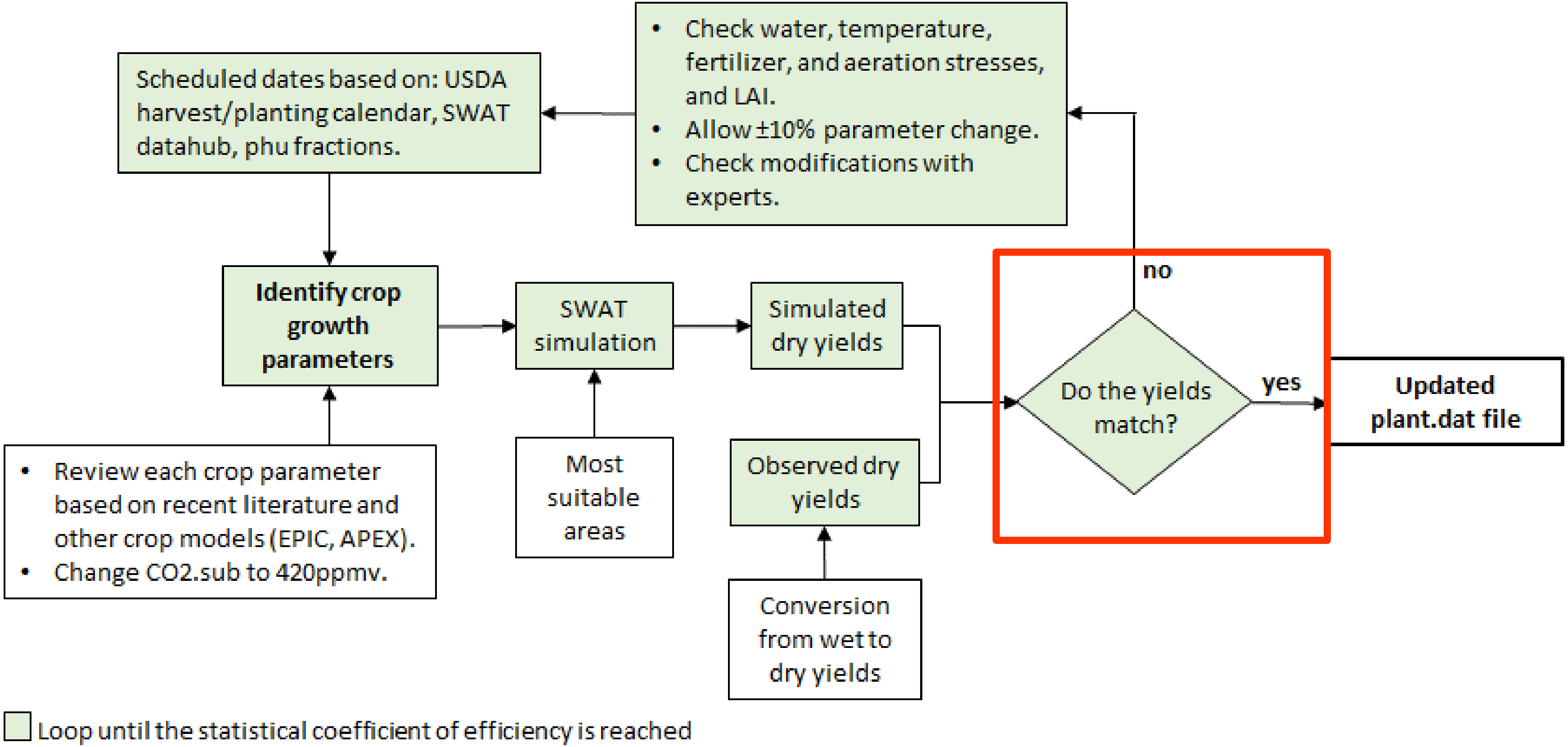
Parameter SWAT code	Parameter description
PLTPFR(1)	Phosphorus uptake emergence
PLTPFR(2)	Phosphorus uptake midseason
PLTPFR(3)	Phosphorus uptake maturity
WSYF	Minimum harvest index
USLE_C	Minimum C factor
GSI	Maximum stomatal conductance
VPDFR	Vapor pressure deficit
FRGMAX	Max Stomatal Conductance 2
WAVP	BIO_E decline

Parameter SWAT code	Parameter description
CO2HI	Elevated CO2 concentration
BIOEHI	CO2HI biomass energy ratio
RSDCO_PL	Daily Residue Decomposition
ALAI_MIN	Minimum Leaf Area Index
BIO_LEAF	Biomass Fraction Leaf
MAT_YRS	Tree Years Maturity
BMX_TREES	Forest Maximum Biomass
EXT_COEF	Light Extinction Coefficient
BMDIEOFF	Biomass Dieoff Fraction

Heat Unit calculation







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Statistical evaluation

To calculate the error:

$$Pbias = \left[\frac{\sum_{t=1}^{n}\left(X_i^{obs} - X_i^{sim}\right)}{\sum_{t=1}^{n}\left(X_i^{obs}\right)}\right] * 100$$

To calculate the acceptable range:

$$Ep = \left[\frac{1}{n}\sum_{s=1}^{n}\left(d_s^2\right)\right]^{\frac{1}{2}}$$

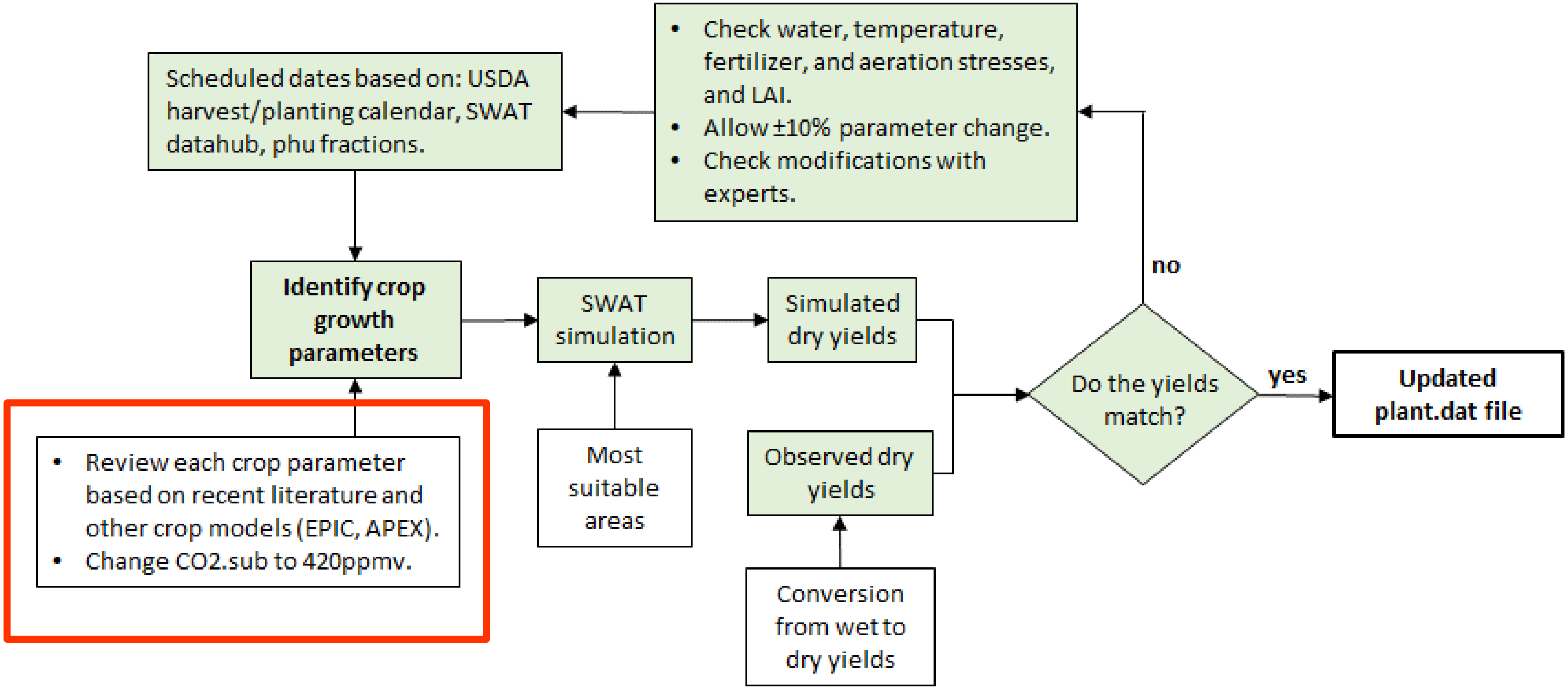
- The formulation is for grouping and propagating error.
- The potential error sources : observed yields (±25%), water content (±5%), epistemic errors (10%) and non-calibrated model errors (±20%).
- Total probable error is determined as a function of these four errors, and is **Ep = 34%**.

Observed fresh to dry yields

Crop variety	Dry yield (ton/ha)	Crop variety	Dry yield (ton/ha)
Apple	5.2	Lettuce	2.2
Blueberries	1.2	Melon	3.0
Broccoli	1.6	Onions	5.4
Cabbage	4.4	Pears	6.0
Carrots	7.5	Potatoes	9.5
Cherries	7.1	Pumpkin	2.9
Collard Greens	0.9	Raspberries	1.1
Sweet Corn	4.6	Spinach	1.5
Cucumber	0.8	Squash	2.1
Dry beans	1.7	Strawberries	4.7
Grapes	3.9	Sweet Potatoes	6.0
Kale	4.6	Tomatoes	5.4

Heat Unit calculation

Crop variety	Heat unit (HU) 10-year average	Crop variety	Heat unit (HU) 10-year average
Apple	1129	Lettuce	1603
Dry Beans	1756	Melon	2186
Blueberries	948	Onions	3827
Broccoli	551	Pears	1256
Cabbage	790	Potatoes	925
Carrots	2288	Pumpkin	898
Cherries	1533	Raspberries	1893
Collard greens	1453	Spinach	539
Sweet corn	2341	Squash	719
Cucumber	1505	Strawberries	1268
Grapes	1205	Sweet potatoes	989
Kale	1290	Tomatoes	1689



Loop until the statistical coefficient of efficiency is reached

Examples

Review each crop parameter based on recent literature, and **other models** (EPIC, APEX)

Parameters	lettuce					
	swat	apex	apex	apex	epic	10%
Radiation use efficiency	23	23	23	19	23	25.3
Harvest index	0.8	0.8	0.8	0.8	0.95	
Max Potential Leaf Area Index	4.2	4.2	4.2	4.2	4.2	
PHU fraction point 1	0.25	25.23	25.23	25.23	25.23	
BLAI fraction point 1	0.23					
PHU fraction point 2	0.4	40.86	40.86	40.86	40.86	
BLAI fraction point 2	0.86					
Growing season decline fraction	1	1	1	1	1	
Maximum canopy height	0.2	0.2	0.2	0.2	0.2	
Maximum root depth	0.6	0.6	0.8	0.8	0.8	
Optimal growth temperature	18	18	18.2	18.2	18.2	
Minimum growth temperature	7	7	0	0	0	
Nitrogen in yield	0.0393	0.0393	0.0394	0.0347	0.0394	
Phosphorus in yield	0.0049	0.0049	0.0049	0.0042	0.0049	
Nitrogen uptake emergence	0.036	0.036	0.05	0.05	0.05	
Nitrogen uptake midseason	0.025	0.025	0.025	0.025	0.025	
Nitrogen uptake maturity	0.021	0.021	0.021	0.021	0.021	
Phosphorus uptake emergence	0.0084	0.0084	0.0084	0.0084	0.0084	
Phosphorus uptake midseason	0.0032	0.0032	0.0032	0.0032	0.0032	
Phosphorus uptake maturity	0.0019	0.0019	0.0019	0.0019	0.0019	
Minimum harvest index	0.01	0.01	0.8	0.8	0.8	
Minimum C factor	0.01					
Maximum stomatal conductance	0.003	0.0025	0.0122	0.0122	0.0122	
Vapor pressure deficit	4					
Max Stomatal Conductance 2	0.75					
BIO_E decline	8	0.5	0.5	0.5	0.5	
Elevated CO2 concentration	660	660.25	660.31	660.26	660.31	
CO2HI biomass energy ratio	25					
Daily Residue Decomposition	0.05					
Minimum Leaf Area Index	0	0.1	0.1	0.1	0.1	
Biomass Fraction Leaf	0					
Tree Years Maturity	0					
Forest Maximum Biomass	0					
Light Extinction Coefficient	0.65					
Biomass Dieoff Fraction	0.1					
Root Shoot Ratio Initial						
Root Shoot Ratio Final						

Examples

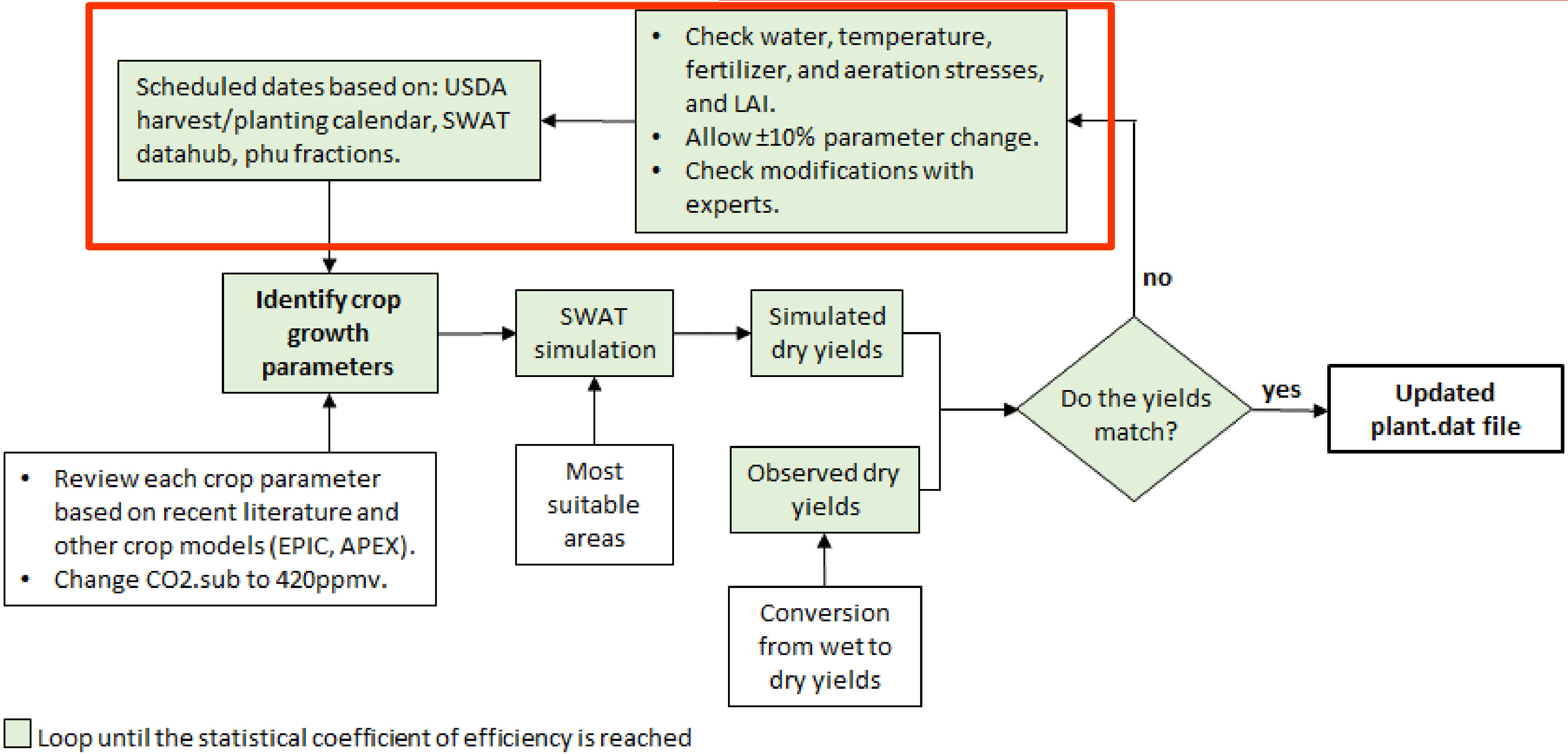
Review each crop parameter based on **recent literature**, **other models**, **similar phenology**.

Parameters	Squash		
	Apex (pumpkin)	suggested by Kim2020 (Straight Neck)	book
Radiation use efficiency	30	25	
Harvest index	0.5	0.64	
Max Potential Leaf Area Index	1.5		
PHU fraction point 1	0.15	0.73	
BLAI fraction point 1	0.01	0.2	
PHU fraction point 2	0.5	0.95	
BLAI fraction point 2	0.95	0.82	
Growing season decline fraction	0.6	0.75	
Maximum canopy height	0.8	0.55	
Maximum root depth	1.1		
Optimal growth temperature	35	25	
Minimum growth temperature	18	15	7.5
Nitrogen in yield	0.0117		
Phosphorus in yield	0.0011		
Nitrogen uptake emergence	0.025		
Nitrogen uptake midseason	0.015		
Nitrogen uptake maturity	0.01		
Phosphorus uptake emergence	0.0053		
Phosphorus uptake midseason	0.0025		
Phosphorus uptake maturity	0.0012		
Minimum harvest index	0.25		
Minimum C factor			
Maximum stomatal conductance	0.007		
Vapor pressure deficit			
Max Stomatal Conductance 2			
BIO_E decline	1		
Elevated CO2 concentration	660.41		
CO2HI biomass energy ratio			
Daily Residue Decomposition			
Minimum Leaf Area Index	1		
Biomass Fraction Leaf			
Tree Years Maturity			
Forest Maximum Biomass			
Light Extinction Coefficient			
Biomass Dieoff Fraction			
Root Shoot Ratio Initial			
Root Shoot Ratio Final			

Examples

Review each crop parameter based on **recent literature**, and other models (EPIC, APEX)

Parameters	Broccoli			
	swat	**apex**	**epic**	**suggested by Kim2021**
Radiation use efficiency	26	26	26	31
Harvest index	0.8	0.8	0.95	0.23
Max Potential Leaf Area Index	4.2	4.2	4.2	4.83
PHU fraction point 1	0.25	0.25	0.25	0.17
BLAI fraction point 1	0.23	0.23	0.23	0.18
PHU fraction point 2	0.4	0.4	0.4	0.67
BLAI fraction point 2	0.86	0.86	0.86	0.62
Growing season decline fraction	1	1	1	0.75
Maximum canopy height	0.5	1.2	1.2	
Maximum root depth	0.6	0.7	0.7	
Optimal growth temperature	18	24	24	16
Minimum growth temperature	4	4	4	0
Nitrogen in yield	0.0512	0.0512	0.0512	
Phosphorus in yield	0.0071	0.0071	0.0071	
Nitrogen uptake emergence	0.062	0.07	0.07	
Nitrogen uptake midseason	0.009	0.05	0.05	
Nitrogen uptake maturity	0.007	0.04	0.04	
Phosphorus uptake emergence	0.005	0.006	0.006	
Phosphorus uptake midseason	0.004	0.004	0.004	
Phosphorus uptake maturity	0.003	0.003	0.003	
Minimum harvest index	0.95	0.8	0.8	
Minimum C factor	0.2			
Maximum stomatal conductance	0.006	0.01	0.01	
Vapor pressure deficit	4			
Max Stomatal Conductance 2	0.75			
BIO_E decline	5	0.1	0.1	
Elevated CO2 concentration	660	660.41	660.41	
CO2HI biomass energy ratio	30			
Daily Residue Decomposition	0.05			
Minimum Leaf Area Index	0	0.1	0.1	
Biomass Fraction Leaf	0			
Tree Years Maturity	0			
Forest Maximum Biomass	0			
Light Extinction Coefficient	0.65			
Biomass Dieoff Fraction	0.1			
Root Shoot Ratio Initial				
Root Shoot Ratio Final				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Examples

Scheduled dates based on: **USDA harvest/planting calendar,** SWAT datahub, phu fractions

Pumpkins for Fresh Market and Processing (continued)

Season and State	Usual Planting Dates		Usual Harvesting Dates		
	Begins	Ends	Begins	Most Active	Ends
Summer					
CA	Apr 1	Jul 31	Aug 1	Sep 1 - Oct 31	Nov 30
Fall					
IL	Jun 1	Jun 25	Sep 1	Oct 10 - Oct 25	Oct 31
MI	Jun 1	Jun 15	Sep 15	Oct 1 - Oct 31	Nov 15
NY	May 25	Jun 30	Sep 10	Sep 20 - Oct 20	Oct 31
OH	May 20	Jun 10	Sep 1	Sep 7 - Oct 31	Oct 31
PA	May 20	Jun 15	Sep 20	Oct 10 - Oct 31	Nov 10

Examples

Scheduled dates based on: USDA harvest/planting calendar, SWAT datahub, **phu fractions**

crop/fe	Operati	phubase	phuacc
COLG	HARV/KILL	0.48	0.62
COLG	HARV/KILL	0.42	0.6
COLG	HARV/KILL	0.45	0.67
COLG	HARV/KILL	0.44	0.6
COLG	HARV/KILL	0.44	0.6
COLG	HARV/KILL	0.45	0.64
COLG	HARV/KILL	0.46	0.65
COLG	HARV/KILL	0.48	0.69
COLG	HARV/KILL	0.39	0.59
COLG	HARV/KILL	0.43	0.61
COLG	HARV/KILL	0.47	0.66
COLG	HARV/KILL	0.42	0.63
COLG	HARV/KILL	0.55	0.71

Yield was too high, before adjustment the phuacc was ~5 (used the 85 days of growing range)

Examples

Check water stress, **temp. stress**, fertilizer stress, aeration stress, **LAI**

Expert "changed the lai-phu curve points to the same as corn. the previous points for squash never allowed the lai to get close to the maximum lai (1.5). at 0.73 fraction of heat units to maturity the lai was 0.2* lai max. at 0.95 (* 1,700) the lai was 0.82 * lai max."

Parameters	Squash		
	Apex (pumpkin)	suggested by Kim2020 (Straight Neck)	book
Radiation use efficiency	30	25	
Harvest index	0.5	0.64	
Max Potential Leaf Area Index	1.5		
PHU fraction point 1	0.15	0.73	
BLAI fraction point 1	0.01	0.2	
PHU fraction point 2	0.5	0.95	
BLAI fraction point 2	0.95	0.82	
Growing season decline fraction	0.6	0.75	
Maximum canopy height	0.8	0.55	
Maximum root depth	1.1		
Optimal growth temperature	35	25	
Minimum growth temperature	18	15	7.5
Nitrogen in yield	0.0117		
Phosphorus in yield	0.0011		
Nitrogen uptake emergence	0.025		
Nitrogen uptake midseason	0.015		
Nitrogen uptake maturity	0.01		
Phosphorus uptake emergence	0.0053		
Phosphorus uptake midseason	0.0025		
Phosphorus uptake maturity	0.0012		
Minimum harvest index	0.25		
Minimum C factor			
Maximum stomatal conductance	0.007		
Vapor pressure deficit			
Max Stomatal Conductance 2			
BIO_E decline	1		
Elevated CO2 concentration	660.41		
CO2HI biomass energy ratio			
Daily Residue Decomposition			
Minimum Leaf Area Index	1		
Biomass Fraction Leaf			
Tree Years Maturity			
Forest Maximum Biomass			
Light Extinction Coefficient			
Biomass Dieoff Fraction			
Root Shoot Ratio Initial			
Root Shoot Ratio Final			

Examples

Allow 10% parameter change

Different values for Pear
Edible Horticultural Crops book

Parameters	Apple			
	swat	apex	epic	10% + book
Radiation use efficiency	15	15	15	13.5
Harvest index	0.1	0.1	0.1	0.09
Max Potential Leaf Area Index	4	4	4	
PHU fraction point 1	0.1	0.1	0.1	
BLAI fraction point 1	0.15	0.15	0.15	
PHU fraction point 2	0.5	0.5	0.5	
BLAI fraction point 2	0.75	0.75	0.75	
Growing season decline fraction	0.99	0.99	0.99	
Maximum canopy height	3.5	3.5	3.5	
Maximum root depth	2	1	1	
Optimal growth temperature	20	22	22	
Minimum growth temperature	7	6	6	7
Nitrogen in yield	0.0019	0.0019	0.0019	
Phosphorus in yield	0.0004	0.0004	0.0004	
Nitrogen uptake emergence	0.006	0.006	0.006	
Nitrogen uptake midseason	0.002	0.002	0.002	
Nitrogen uptake maturity	0.0015	0.0015	0.0015	
Phosphorus uptake emergence	0.0007	0.0007	0.0007	
Phosphorus uptake midseason	0.0004	0.0004	0.0004	
Phosphorus uptake maturity	0.0003	0.0003	0.0003	
Minimum harvest index	0.05	0.05	0.05	
Minimum C factor	0.001			
Maximum stomatal conductance	0.007	0.007	0.007	
Vapor pressure deficit	4			
Max Stomatal Conductance 2	0.75			
BIO_E decline	3	1	1	
Elevated CO2 concentration	660	660	660	
CO2HI biomass energy ratio	20			
Daily Residue Decomposition	0.05			
Minimum Leaf Area Index	0.75	1	1	
Biomass Fraction Leaf	0.3			
Tree Years Maturity	10			
Forest Maximum Biomass	500			
Light Extinction Coefficient	0.65			
Biomass Dieoff Fraction	0.1			
Root Shoot Ratio Initial				
Root Shoot Ratio Final				

10%

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Final parameters example

Crop	IDC[1]	Primary model data set source	Modified plant parameters based on model testing and other data sources[2]
Apple	7	SWAT	BIO_E ([85] and ±10% change), HVSTI (±10% change), T_OPT (APEX & EPIC), T_BASE [85,87]
Blueberry	6	APEX	WSYF, WAVP, HVSTI (modeling team expertise), T_OPT & T_BASE [85]
Broccoli	5	SWAT	BIO_E, HVSTI, BLAI, FRGRW1, FRGRW2, LAIMX1, LAIMX2, DLAI, T_OPT, T_BASE and WSYF ([93] and modeling team expertise)
Cabbage	5	SWAT	BIO_E, FRGRW1, FRGRW2, LAIMX1, LAIMX2, DLAI, CHTMX, T_OPT, T_BASE and WSYF ([94] and modeling team expertise)
Carrot	4	SWAT	BIO_E, BLAI, WSYF (±10% change); HVSTI [95] & T_BASE [85]
Cherry	7	SWAT[3]	T_OPT & T_BASE [85]
Collard greens	5	APEX	No further modifications

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Simulated yields

Crops	Yield (ton/ha)			Crops	Yield (ton/ha)		
	Observed	Simulated	Pbias (%)		Observed	Simulated	Pbias (%)
Apple	5.2	6.7	29.3	**Lettuce**	2.2	1.6	-25.6
Blueberries	1.2	1.0	-16.6	**Melon**	3.0	2.2	-25.9
Broccoli	1.6	2.0	24.6	**Onions**	5.4	7.1	32.9
Cabbage	4.4	4.0	-8.9	**Pears**	6.0	5.9	-0.1
Carrots	7.5	9.7	29.6	**Potatoes**	9.5	7.3	-23.6
Cherries	7.1	8.6	21.2	**Pumpkin**	2.9	2.2	-24.8
Collard greens	0.9	1.2	33.1	**Raspberries**	1.1	1.8	8.1
Sweet corn	4.6	5.8	26.1	**Spinach**	1.5	1.8	21.3
Cucumber	0.8	0.7	-12.3	**Squash**	2.1	2.6	23.5
Dry beans	1.7	1.4	-21.1	**Strawberries**	4.7	4.5	-3.7
Grapes	3.9	3.3	-14.1	**Sweet potatoes**	6.0	5.1	-13.8
Kale	4.6	5.7	21.2	**Tomatoes**	5.4	6.8	26.3

Conclusion & Highlights

- The plant parameters established in this study will be used to support Iowa UrbanFEWS SWAT simulation.
- These parameters could also be used for other possible future applications in Iowa and similar production areas in the western Corn Belt region.
- Additional testing of the plant parameters is recommended for Iowa conditions as additional observed data becomes available.

Caution should be used in extrapolating these parameter values to other regions. It is recommended that:

- Users consult the literature to determine what SWAT fruit and vegetable parameters have been used for specific regions of interest, and
- Testing should be performed to ensure that the most reliable choice of parameter values are used for SWAT fruit and vegetable applications in other regions.

Thank you!