Fruit & Vegetable Supply Chains

Climate Adaptation & Mitigation Opportunities

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Protocol for US Fruit and Vegetable Crop Modeling

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BACKGROUND

Fruits and vegetables are important parts of a healthy, balanced diet in our daily lives. Climate change could impact fruit and vegetable production in the United States (US). Fruit and vegetable production could decline or increase in the current production areas. There could also be opportunities to produce fruit and vegetables in new areas of the US under future climate scenarios. Multi-model simulations (including multi-crop models and statistical models) needed to be conducted for potatoes, tomatoes, sweet corn, green (snap) beans, carrots, spinach, strawberries, and oranges, following standard protocols based on the AgMIP approach and protocols (https://agmip.org/).

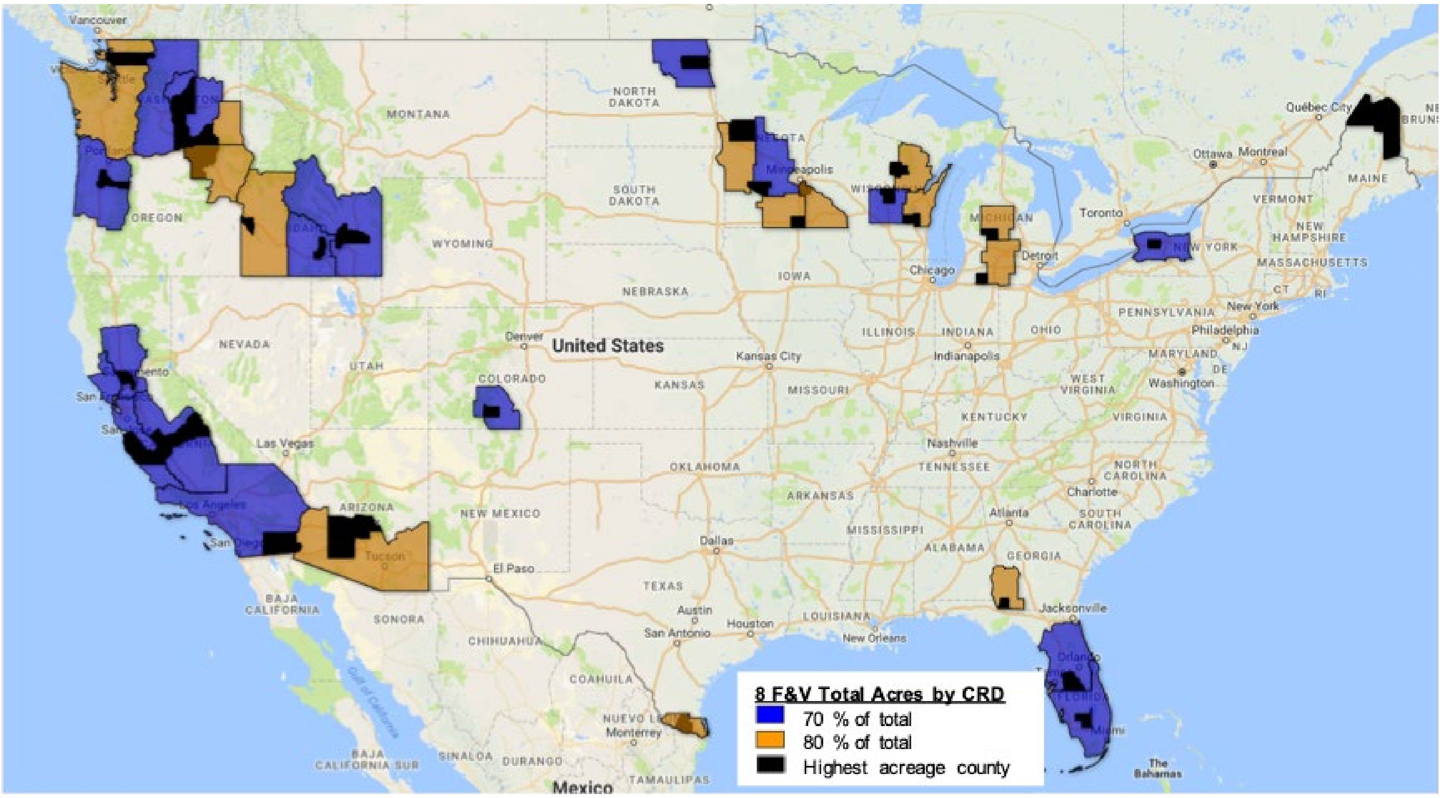
GOAL

To develop a protocol to assess the climate change impact on fruit and vegetable production and potential adaptations, including possible shifts in production area in the United States.

SELECTION OF REPRESENTATIVE COUNTIES

Eight fruit and vegetable crops are studied within the NIFA-funded project (Award #: 2017-68002-26789) "Fruit & Vegetable Supply Chains: Climate Adaptation & Mitigation Opportunities," including potatoes, tomatoes, carrots, green (snap) beans, spinach, strawberries, sweet corn, and oranges. For efficiency, counties were selected to represent all eight crops. The total production acreage for all eight crops was tabulated for all Crop Reporting Districts (CRDs), using data from the most recent USDA AgCensus (2012). The CRDs were then sorted in descending order, choosing the highest acreage CRDs necessary to capture 80% of all acreage for these eight crops. This resulted in a list of 32 CRDs (31 CRDs plus St. Johns, FL for its importance in potato production), and the counties having the highest target crop acreage within each of these CRDs were then selected for all subsequent open-field crop modeling (see Figure 1 & Table 1).

Figure 1: Crop Reporting Districts (CRDs) making up 70% and 80% of total target crop acreage, as well as the highest target crop acreage county in each CRD.



Source: USDA 2012 Ag Census (quickstats.nass.usda.gov), NASS CDL, WAEES Fill-in

Table 1: Selected counties[1]

No.	State	State Crop Reporting District (CRD)	Target Crop Area in the CRD (ha)	County	Target Crop Area in the County (ha)
1	Arizona	AZ80	7,223	Maricopa	3,173
2	California	CA51	186,624	Fresno	59,003
3		CA80	35,381	Imperial	11,168
4		CA40	24,658	Monterey	15,228
5		CA50	32,326	Yolo	16,223
6	Colorado	CO80	22,900	Rio Grande	7,438
7	Florida	FL80	181,203	Hendry	41,242
8		FL50	64,226	Polk	29,880
9		FL50	64,226	St. Johns[2]	6,020
10	Georgia	GA70	10,002	Decatur	6,264
11	Idaho	ID90	100,707	Bingham	31,262
12		ID70	7,275	Canyon	3,143
13		ID80	35,569	Minidoka	12,770
14	Maine	ME10	23,205	Aroostook	23,205
15	Michigan	MI50	9,746	Montcalm	7,230
16		MI80	6,240	St. Joseph	3,748

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[1] Not all eight target crops (carrots, green beans, oranges, potatoes, spinach, strawberries, sweet corn, and tomatoes) can be grown in all 31 of these counties, except for oranges. Counties where open-field production is not possible (e.g., oranges in northern areas) are not included in the modeling protocol for that crop.

[2] St. Johns County included to ensure representative modeling of potatoes in northern Florida.

No.	State	State Crop Reporting District (CRD)	Target Crop Area in the CRD (ha)	County	Target Crop Area in the County (ha)
17	Minnesota	MN90	12,464	Dakota	3,505
18		MN80	12,763	Freeborn	2,512
19		MN40	6,460	Otter Tail	4,266
20		MN50	22,859	Renville	9,813
21	New York	NY40	19,728	Genesee	4,295
22	North Dakota	ND30	25,906	Walsh	13,448
23	Oregon	OR10	16,180	Marion	6,932
24		OR30	10,380	Umatilla	7,788
25	Texas	TX97	7,291	Hidalgo	6,601
26	Washington	WA20	27,984	Benton	25,024
27		WA50	63,672	Grant	30,033
28		WA10	9,899	Skagit	5,515
29		WA90	7,152	Walla Walla	6,990
30	Wisconsin	WI60	6,307	Fond du Lac	2,052
31		WI30	9,361	Langlade	6,596
32		WI50	55,503	Portage	26,549

CROP MODELS/STATISTICAL MODEL

Up to five crop models and one statistical model (Table 2) were used for some of the crops, such as potatoes, and less for others. The models include SIMPLE (developed at University of Florida) (Zhao et al. 2019), CropSyst (developed at Washington State University) (Stöckle et al. 1994; Stöckle et al. 2003; Stöckle et al. 2014), LINTUL-POTATO-DSS (developed at Wageningen University) (Haverkort et al. 2015), EPIC (via USDA collaboration), DSSAT CSM-Substor-Potato (Raymundo et al. 2017), and a statistical model (Li et al. 2019).

Table 2: Crop models used for fruit and vegetable simulations.

No.	Crop Model/Statistical Model	Reference
1	SIMPLE	Zhao et al. (2019)
2	CropSyst	Stöckle et al. (1994)
3	LINTUL-POTATO-DSS	Haverkort et al. (2015)
4	EPIC	Williams et al. (1989)
5	CSM-Substor-Potato	Raymundo et al. (2017)
6	Statistical model	Li et al. (2019)

CROP MODEL/STATISTICAL MODEL PARAMETERIZATION

a. Crop models are parameterized with available field experimental data. The statistical model is trained with a USDA NASS dataset (NASS 2017).
b. The parameterizations for crop models depend on crop specific characteristics (see details in the Appendix for each crop). For example, potatoes in the US are harvested well before the natural maturity of the crop by killing the vines before maturity. The accumulated temperature requirement of a model for the baseline is set for each county (assuming different maturity types for each county), assuming that canopy cover for potato will still be about 80% at the harvest date. This needs to be redefined for each new crop.
c. Crop models need to be calibrated to the observed yield data shown in Table A1 for each crop. The estimated impact from the statistical model was applied to the field-experimental-based-corrected district yields (e.g., for potatoes in Table A1), and the average simulated baseline yield from SIMPLE and CropSyst for other crops (e.g., for tomatoes).
d. Crop-specific planting dates for the baseline and future scenarios are shown in Table A2 for each crop (see Table legend for details).
e. Full irrigation is assumed to have been applied to avoid/minimize any water stress. It is assumed that there are no nutrient limitations.

SOIL DATA

Soil data is not required for crop modeling here, which assumes the complete absence of any water or nutrient deficit stress (fully irrigated and fully fertilized conditions).

CLIMATE DATA

Daily weather data is available for each of the 32 counties (a 4 km x 4 km grid cell used per location). The weather data include separate files for the historical period (1980-2016) and one for future periods (2020-2099). The baseline period is 1981-2010 and the future periods for 2030s is 2021-2050 and for 2050s is 2041-2070. The weather files include maximum and minimum temperature, precipitation, solar radiation, maximum and minimum relative humidity, and wind speed. Because GCMs tend to project up to 8% higher solar fluxes than baseline data depending on the US location, solar radiation data was adjusted for minimum change compared to baseline data. The daily weather data were extracted from the Web Accessible Folder (http://cloud.insideidaho.org/webservices.html#waf) maintained by the University of Idaho, based on the methodology described in Brown (2012) and Abatzoglou (2013).

The historical gridded daily weather data are based on a methodology that blends desirable attributes of gridded climate data and desirable temporal attributes of regional-scale reanalysis and daily gauge-based precipitation to derive a high-resolution gridded surface meteorological dataset covering the continental United States (Abatzoglou 2013). For future weather, climate simulations from five global climate models (GCMs; Table 3) in the Coupled Model Intercomparison Project, Phase 5 (CMIP5) were statistically downscaled over the contiguous United States using the Multivariate Adaptive Constructed Analogs (MACA) method with a joint bias correction of daily temperature and precipitation (Abatzoglou and Brown 2012). Downscaled data were trained using the 1/24th degree resolution gridded surface meteorological dataset of Abatzoglou (2013). Note: Rainfall is not required as the modeling does not consider the possibility of water stress.

CO_2 FERTILIZATION EFFECT

It is generally accepted that higher future atmospheric CO_2 concentrations will stimulate growth. However, the magnitude of the effect is subject to uncertainty and would likely be constrained under nutrient limitations (Kimball 2016). As most fruit and vegetables in the US receive adequate fertilizer and irrigation, such constraints of the CO_2 fertilizer effect are unlikely for the future scenarios considered within this project. The yearly changing atmospheric CO_2 concentrations for baseline (1981-2010) and future periods (2030s and 2050s) under the RCP8.5 scenario are shown in Table 4. These annual CO_2 concentrations are used for the baseline and the future scenarios. For the no-future-CO_2 simulations, 360 ppm (concentration in 1995, half-way through the baseline period) is used for each year in the future, to allow quantification of the impact from future elevated CO_2.

SIMULATION OF CLIMATE CHANGE IMPACT AND ADAPTATION

Climate change and adaptation scenarios are shown in Table 5. Planting dates for baseline (and future without adaptation) and future (with adaptation) scenarios are supplied in Table A2. The season length for the baseline and future scenarios is kept the same and is also supplied in Table A2.

Table 3: General circulation models (GCM) used for future scenarios.

No.	GCM
1	GFDL-ESM2M
2	HadGEM2-ES365
3	IPSL-CM5A-LR
4	MIROC-ESM-CHEM
5	NorESM1-M

Table 4: Yearly atmospheric CO_2 concentration for the baseline (1981-2010) and future periods (2030s and 2050s) under RCP8.5 scenario (Riahi et al. 2011).

Baseline		2030s		2050s	
Year	CO_2 (ppm)	Year	CO_2 (ppm)	Year	CO_2 (ppm)
1981	340	2021	419	2041	494
1982	341	2022	422	2042	499
1983	342	2023	425	2043	504
1984	344	2024	428	2044	508
1985	345	2025	431	2045	513
1986	347	2026	435	2046	519
1987	349	2027	438	2047	524
1988	351	2028	442	2048	529
1989	352	2029	445	2049	535
1990	354	2030	449	2050	541
1991	355	2031	452	2051	546
1992	356	2032	456	2052	552
1993	357	2033	460	2053	558
1994	358	2034	464	2054	564
1995	360	2035	468	2055	571
1996	361	2036	472	2056	577
1997	363	2037	476	2057	583
1998	365	2038	481	2058	590
1999	367	2039	485	2059	597
2000	369	2040	489	2060	604
2001	370	2041	494	2061	611
2002	373	2042	499	2062	618
2003	375	2043	504	2063	625
2004	377	2044	508	2064	632
2005	379	2045	513	2065	639
2006	381	2046	519	2066	647
2007	383	2047	524	2067	654
2008	385	2048	529	2068	662
2009	387	2049	535	2069	669
2010	389	2050	541	2070	677

Table 5: Protocol for US fruit and vegetable simulations.

No.	Scenarios	Time Period	Planting Dates
1	Baseline	1981-2010	From Table A2
2	2030sNoAdaptation without elevated CO_2	2021-2050	Same as baseline
3	2050sNoAdaptation without elevated CO_2	2041-2070	Same as baseline
4	2030sNoAdaptation with elevated CO_2	2021-2050	Same as baseline
5	2050sNoAdaptation with elevated CO_2	2041-2070	Same as baseline
6	2030sAdaptation with elevated CO_2	2021-2050	From Table A2
7	2050sAdaptation with elevated CO_2	2041-2070	From Table A2

MULTI-MODEL ENSEMBLE

Each model will be used to simulate the baseline (1 simulation), as well as the impact and adaptation for two future periods (without and with adaptation) (Table 5), with five GCMs (Table 3) and with elevated atmospheric CO_2. The future impact, without the adaption, will also be simulated without elevated atmospheric CO_2 to quantify the CO_2 impact. The total number of simulations per model and grid cell (or location) and each for 30 years is: 31 = 1 baseline + 5GCMs x 2030s with elevated CO_2 + 5GCMs x 2050s with elevated CO_2 + 5GCMs x 2030s without elevated CO_2 + 5GCMs x 2050s without elevated CO_2 + 5GCMs x 2030s with elevated CO_2 and adaptation + 5GCMs x 2050s with elevated CO_2 + adaptation). Note: the future adaptation will not be simulated without elevated CO_2.

The ensemble-based yield and crop transpiration impact are calculated using the following steps:

1. Calculate the simulated mean dry matter yield for climate change scenarios across 30 years (1981-2010) per single CM-GCM at each county (grid cell/location).
2. Calculate the simulated mean dry matter yield for climate change scenarios across 30 years (2021-2050 and 2041-2070 with and without adaptation) per single CM-GCM at each county. The without adaptation needs to also be simulated with 360 ppm CO_2, to allow the calculation of the future CO_2 effect.
3. Calculate the relative dry matter yield impact (%) per single CM and per GCM for each county, region, and the whole US. Note that CMs and GCMs simulation results must be kept separate at this stage for calculating uncertainties across CMs and GCMs.
4. The mean of the CMs x GCMs is then considered as the model ensemble median, with 25% and 75% tiles quantifying the uncertainty range.

OUTPUT

Modelers supply annual dry matter yield (at 0% moisture), total biomass (all above-ground biomass plus yield at 0% moisture), and accumulated crop transpiration from sowing to harvest. All the crop models supply dry matter yield results, and all models except the statistical model supply total biomass results. The crop transpiration results are supplied by CropSyst only. All simulated annual data are added to the supplied template (one file with all simulations per crop) and sent to the University of Florida for processing.

The simulated data are used to calculate: % change under future climates with and without adaptation and the effect of elevated CO_2. N, P, and K uptake are calculated after the crop simulations at the University of Florida, based on simulated yield and standard nutrient concentrations from the literature (modelers did not need to calculate this). We considered a lower nutrient concentration under elevated atmospheric CO_2 (Loladze 2014).

N/P/K taken up by a crop are estimated as the N/P/K concentrations from yield at harvest. All yields are expressed as dry matter (DM). The N, P, and K uptake (kg N/P/K per ha) is calculated as below:

$$N_{uptake} = N_{Yield} \times Yield \times \left[1 + \frac{(CO_2 - 364) \times fN_{Yield}}{100}\right] \quad \textbf{(1)}$$

$$P_{uptake} = P_{Yield} \times Yield \times \left[1 + \frac{(CO_2 - 364) \times FP_{Yield}}{100}\right] \quad \textbf{(2)}$$

$$K_{uptake} = K_{Yield} \times Yield \times \left[1 + \frac{(CO_2 - 364) \times FK_{Yield}}{100}\right] \quad \textbf{(3)}$$

where $N/P/K_{uptake}$ is the N/P/K taken up by the yield (kg N/P/K per ha). $N/P/K_{Yield}$ represent the fraction of N/P/K in the dry matter of yield. $F\text{-}N/P/K_{Yield}$ represents the CO_2 effect on N concentration of yield (%/ppm). CO_2 is the atmospheric CO_2 concentration (ppm).

The parameter values for the equations above are shown in Table A3 for each crop (see Table legend for details). The uncertainty range aggregated at the county, region, and national scale for impact and adaptation for each future period relative to the baseline period is calculated from the simulated data.

Any proportion of harvestable product left in the field (e.g., due to size or technology) are calculated elsewhere.

OUTPUT FILE NAMING

Once the simulation runs are completed, the results are saved into the provided template ("Template-summary.xlsx"). If the model does not simulate one of the outputs, "na" is added in each of the cells. The template files are renamed using the 2-LETTER model and 2-LETTER crop code from Table 6.

Result file names: ModelCode-CropCode.xlsx. (e.g., the result file of the CropSyst model for potato should be CS-po.xlsx)

Table 6: 2-LETTER Code for models and crops.

No.	Crop Model	2-Letter Name Code	Crop	2-Letter Name Code
1	SIMPLE	SI	potatoes	po
2	CropSyst	CS	tomatoes	to
3	LINTUL-POTATO-DSS	LI	sweet corn	sw
4	EPIC	EP	orange	or
5	DSSAT CSM-Substor-Potato	DC	carrots	ca
6	Statistical Model	ST	green beans	gb
7			strawberry	st
8			spinach	sp

SOURCE OF WEATHER DATA AND OUTPUT TEMPLATE

Daily weather data is available for each of the 32 counties (a 4 km x 4 km grid cell) in a zip-file. The zip file includes a separate folder with weather data for the historical period (1980-2016) for the 32 locations and five folders, one for each GCM, for the future periods (2020-2099), with weather files for 32 locations. The weather file uses up to the first 6 letters from the county name for the file name.

All weather input data needed for the simulations are available at:

https://www.dropbox.com/sh/z8nnlgxzmgjwe30/AADfWM7vNLzmR6Xb7xnG-jzga?dl=0

This file depository also supplies a file for the yearly atmospheric CO_2 concentration and a template file for the output simulations.

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Appendix: Potato *(Solanum tuberosum)*

POTATO-SPECIFIC PARAMETERIZATION

Potatoes in the US are harvested well before the natural maturity of the crop by killing the vines. The accumulated temperature requirement of a model for the baseline are set for each county (assuming different maturity types for each county), assuming that canopy cover for potato is about 80% at the vine killing time and harvest date. Crop models are calibrated (harvest index is kept between 0.5 and 0.9) to the reported gridded yield data from the year 2000 from Monfreda et al. (2008), which were adjusted with yield data from variety trials from recent years (Table A1). For potato tuber, 20% of fresh weight is considered as dry matter.

Table A1 - Potato*: Baseline potato tuber dry weight (the corrected yields in the last column used for calibration) for the counties selected for modeling. Observed yields from Manfredo et al. (2008) for year 2000 were increased by 3.6 t/ha to reflect yield potential of more recent years, based on a comparison of several variety trial yields from recent years with the year 2000 data. As Fresno and Yolo (CA) had extremely low reported yields in Manfredo et al. (2008), the yields for these two counties were replaced with nearby variety trial yields. The statistical model uses the baseline observed yield date for future climate impact assessments.*

No.	State	County	Observed Tuber Dry Weight (t/ha)	Corrected Tuber Dry Weight (t/ha) (for calibration)
1	Arizona	Maricopa	7.26	10.86
2	California	Fresno	2.62	9.53
3	California	Imperial	7.47	11.07
4	California	Monterey	6.58	10.18
5	California	Yolo	2.75	9.53
6	Colorado	Rio Grande	8.53	12.13
7	Florida	Hendry	6.42	10.02
8	Florida	Polk	5.30	8.90
9	Florida	St. Johns	5.29	8.89
10	Georgia	Decatur	3.51	7.11
11	Idaho	Bingham	8.02	11.62
12	Idaho	Canyon	9.71	13.31
13	Idaho	Minidoka	9.26	12.86
14	Maine	Aroostook	5.65	9.25
15	Michigan	Montcalm	7.58	11.18
16	Michigan	St. Joseph	6.81	10.41
17	Minnesota	Dakota	3.25	6.85
18	Minnesota	Freeborn	6.49	10.09
19	Minnesota	Otter Tail	8.51	12.11
20	Minnesota	Renville	7.95	11.55
21	New York	Genesee	5.93	9.53
22	North Dakota	Walsh	4.49	8.09
23	Oregon	Marion	6.49	10.09
24	Oregon	Umatilla	13.33	16.93
25	Texas	Hidalgo	4.34	7.94
26	Washington	Benton	13.95	17.55
27	Washington	Grant	13.35	16.95
28	Washington	Skagit	4.59	8.19
29	Washington	Walla Walla	14.38	17.98
30	Wisconsin	Fond du Lac	2.06	5.66
31	Wisconsin	Langlade	7.72	11.32
32	Wisconsin	Portage	8.87	12.47

Table A2 - Potato: *Baseline and future potato planting dates for the adaptation scenarios. For future scenarios without adaptation, the planting dates are the same as for the baseline period. The planting date is applied to each year at a location. Planting dates are determined based on a 15-day window above a base mean temperature of 13 °C. The potato season length data for the baseline and future scenarios are from Sacks et al. (2010). The season length (days from sowing to harvest) is the same for baseline and future scenarios, without and with adaptation. Use the season length to calculate the harvest dates.*

No.	State	County	Temperature-Based Planting Date (Day of Year)			Season Length (Days)
			Baseline	2030sAdaptation	2050sAdaptation	Baseline and Future Scenarios
1	Arizona	Maricopa	21	9	4	120
2	California	Fresno	64	45	32	120
3	California	Imperial	9	4	2	120
4	California	Monterey	51	24	13	120
5	California	Yolo	67	47	34	120
6	Colorado	Rio Grande	148	133	124	131
7	Florida	Hendry	2	1	1	110
8	Florida	Polk	3	2	2	110
9	Florida	St. Johns	8	7	4	110
10	Georgia	Decatur	26	18	15	130
11	Idaho	Bingham	138	118	110	140
12	Idaho	Canyon	120	98	87	140
13	Idaho	Minidoka	134	115	106	140
14	Maine	Aroostook	149	135	128	155
15	Michigan	Montcalm	132	117	112	114
16	Michigan	St. Joseph	118	108	104	114
17	Minnesota	Dakota	124	112	108	107
18	Minnesota	Freeborn	125	113	109	127
19	Minnesota	Otter Tail	134	123	118	127
20	Minnesota	Renville	123	113	110	127
21	New York	Genesee	125	112	107	110
22	North Dakota	Walsh	130	118	114	125
23	Oregon	Marion	127	105	96	130
24	Oregon	Umatilla	116	96	88	153
25	Texas	Hidalgo	3	2	2	110
26	Washington	Benton	117	97	89	148
27	Washington	Grant	125	106	98	148
28	Washington	Skagit	136	115	103	125
29	Washington	Walla Walla	115	94	83	148
30	Wisconsin	Fond du Lac	127	114	109	119
31	Wisconsin	Langlade	137	122	118	139
32	Wisconsin	Portage	130	116	111	139

Table A3 - Potato: *N/P/K concentration (%) of dry matter weight (kg DM/ha) of yield, and the CO_2 effects on N/P/K concentrations. The N concentrations dry matter of yield are from Prasad et al. (2015). The P and K concentrations are estimated by a nutrient concentration ratio of N to P and K) after Gugala et al. (2015) and HAIFA (*https://www.haifa-group.com/crop-guide/field-crops/crop-guide-potato/nutrients-growing-potatoes*). The CO_2 effects on N/P/K concentrations are after Loladze (2014).*

Crop Component	N (%)	P (%)	K (%)	FN (%/ppm)	FP (%/ppm)	FK (%/ppm)
Yield	1.70	0.17	2.55	-0.01592	-0.01095	-0.01095

N: Nitrogen content (%) of dry matter yield
P: Phosphorus content (%) of dry matter yield
K: Potassium content (%) of dry matter yield

FN: CO_2 effects on nitrogen content of dry matter yield (%/ppm)
FP: CO_2 effects on phosphorus content of dry matter yield (%/ppm)
FK: CO_2 effects on potassium content of dry matter yield (%/ppm)

Appendix B: Tomato *(Solanum lycopersicum)*

TOMATO-SPECIFIC PARAMETERIZATION

Tomatoes are harvested when a thermal time of 1214 degree-days (DD) is reached (Tbase = 10 °C), which has been found to work well for processing tomatoes in the most productive California counties (Pathak & Stoddard, 2018). If by harvest the thermal time achieved is 1214 DD, then the harvest index is 0.63 for standard. However, in some colder regions, the tomato season will stop if the daily temperature for 7 consecutive days is less than 10 °C. Moreover, if the daily temperature for 14 consecutive days is less than 10 °C, the harvest index at harvest will be reduced and eventually becomes zero. An adjustment factor is used to adjust the standard harvest index, which is obtained from the linear relationships between the harvest indexes and degree-days. The adjustment factor multiplies the standard harvest index to yield the actual harvest index. For tomatoes, 6% of fresh weight is considered as dry matter.

Table A2 - Tomato: *Baseline and future tomato planting dates for the adaptation scenarios. For future scenarios without adaptation, the planting dates are the same as for the baseline period. The planting date will be applied to each year at a location. Planting dates are determined based on a 15-day window above a base mean temperature of 15 °C*

No.	State	County	Temperature-Based Planting Date (Day of Year)		
			Baseline	2030sAdaptation	2050sAdaptation
1	Arizona	Maricopa	44	25	15
2	California	Fresno	83	67	55
3	California	Imperial	25	13	8
4	California	Monterey	104	67	47
5	California	Yolo	87	70	60
6	Colorado	Rio Grande	160	148	138
7	Florida	Hendry	4	2	2
8	Florida	Polk	6	5	3
9	Florida	St. Johns	19	15	11
10	Georgia	Decatur	44	33	29
11	Idaho	Bingham	149	131	123
12	Idaho	Canyon	134	112	103
13	Idaho	Minidoka	148	129	120
14	Maine	Aroostook	162	147	140
15	Michigan	Montcalm	141	128	123
16	Michigan	St. Joseph	134	119	114
17	Minnesota	Dakota	135	122	116
18	Minnesota	Freeborn	136	123	119
19	Minnesota	Otter Tail	145	133	129
20	Minnesota	Renville	134	122	118
21	New York	Genesee	137	123	117
22	North Dakota	Walsh	138	128	125
23	Oregon	Marion	143	132	121
24	Oregon	Umatilla	131	118	107
25	Texas	Hidalgo	9	6	4
26	Washington	Benton	132	119	109
27	Washington	Grant	137	126	116
28	Washington	Skagit	160	141	123
29	Washington	Walla Walla	130	113	104
30	Wisconsin	Fond du Lac	138	124	119
31	Wisconsin	Langlade	151	134	130
32	Wisconsin	Portage	141	127	123

Table A3 - Tomato: *N/P/K concentration (%) of dry matter weight (kg DM/ha) of yield, and the CO_2 effects on N/P/K concentrations. The N concentrations dry matter of yield are from Prasad et al. (2015). The P and K concentrations are estimated by a nutrient concentration ratio of N to P and K) after Gugala et al. (2015) and HAIFA (*https://www.haifa-group.com/crop-guide/field-crops/crop-guide-potato/nutrients-growing-potatoes*). The CO_2 effects on N/P/K concentrations are after Loladze (2014).*

Crop Component	N (%)	P (%)	K (%)	FN (%/ppm)	FP (%/ppm)	FK (%/ppm)
Yield	2.91	0.72	4.43	-0.0298	-0.0666	-0.0008

N: Nitrogen content (%) of dry matter yield
P: Phosphorus content (%) of dry matter yield
K: Potassium content (%) of dry matter yield

FN: CO_2 effects on nitrogen content of dry matter yield (%/ppm)
FP: CO_2 effects on phosphorus content of dry matter yield (%/ppm)
FK: CO_2 effects on potassium content of dry matter yield (%/ppm)

Sweet Corn *(Zea mays convar)*

SWEET CORN-SPECIFIC PARAMETERIZATION

To establish a reference cultivar to be used in all 32 counties, we use Benton, WA as the calibration point. Washington has the largest yields in the US, and it is the leading producer of sweet corn for processing, closely competing with Minnesota. The reference is a mid-season cultivar with the following characteristics.

Number of days from emergence to reach significant phenological stages:

Begin Silking	60 days
Begin Grain Filling	68 days
Harvest (70% Moisture)	85 days

Average dry yield should be around 7,000 kg/ha, with an average harvest index of 0.45. For sweet corn, 30% of fresh weight is considered as dry matter. The average number of days to silking will have some fluctuation in the 32 counties depending on planting dates and weather conditions. However, the period from silking to harvest should be constrained to a maximum of 25 days.

Table A2 - Sweet Corn: *Baseline and future sweet corn planting dates for the adaptation scenarios. For future scenarios without adaptation, the planting dates are the same as for the baseline period. The planting date will be applied to each year at a location. Planting dates are determined based on a 15-day window above a base mean temperature of 15 °C.*

No.	State	County	Temperature-Based Planting Date (Day of Year)		
			Baseline	2030sAdaptation	2050sAdaptation
1	Arizona	Maricopa	44	25	15
2	California	Fresno	83	67	55
3	California	Imperial	25	13	8
4	California	Monterey	104	67	47
5	California	Yolo	87	70	60
6	Colorado	Rio Grande	160	148	138
7	Florida	Hendry	4	2	2
8	Florida	Polk	6	5	3
9	Florida	St. Johns	19	15	11
10	Georgia	Decatur	44	33	29
11	Idaho	Bingham	149	131	123
12	Idaho	Canyon	134	112	103
13	Idaho	Minidoka	148	129	120
14	Maine	Aroostook	162	147	140
15	Michigan	Montcalm	141	128	123
16	Michigan	St. Joseph	134	119	114
17	Minnesota	Dakota	135	122	116
18	Minnesota	Freeborn	136	123	119
19	Minnesota	Otter Tail	145	133	129
20	Minnesota	Renville	134	122	118
21	New York	Genesee	137	123	117
22	North Dakota	Walsh	138	128	125
23	Oregon	Marion	143	132	121
24	Oregon	Umatilla	131	118	107
25	Texas	Hidalgo	9	6	4

No.	**State**	**County**	**Temperature-Based Planting Date (Day of Year)**		
			Baseline	**2030sAdaptation**	**2050sAdaptation**
26	Washington	Benton	132	119	109
27	Washington	Grant	137	126	116
28	Washington	Skagit	160	141	123
29	Washington	Walla Walla	130	113	104
30	Wisconsin	Fond du Lac	138	124	119
31	Wisconsin	Langlade	151	134	130
32	Wisconsin	Portage	141	127	123

Table A3 - Sweet Corn: *N/P/K concentration (%) of dry matter weight (kg DM/ha) of yield, and the* CO_2 *effects on N/P/K concentrations. The ratios of N/P/K concentrations to the dry matter of yield are after Canatoy et al. (2018). The* CO_2 *effects on N/P/K concentrations are after Loladze (2014).*

Crop Component	**N (%)**	**P (%)**	**K (%)**	**FN (%/ppm)**	**FP (%/ppm)**	**FK (%/ppm)**
Yield	3.21	0.52	1.40	0.0827	-0.0172	-0.0008

N: Nitrogen content (%) of dry matter yield
P: Phosphorus content (%) of dry matter yield
K: Potassium content (%) of dry matter yield

FN: CO_2 effects on nitrogen content of dry matter yield (%/ppm)
FP: CO_2 effects on phosphorus content of dry matter yield (%/ppm)
FK: CO_2 effects on potassium content of dry matter yield (%/ppm)

Green Bean *(Phaseolus vulgaris)*

GREEN BEAN-SPECIFIC PARAMETERIZATION

To establish a reference crop to be used in all 32 counties, we use Fond du Lac, WI as the calibration point. Wisconsin dominates the production of green beans in the US, with larger production than the next four leading states combined. We focus on bush varieties (not climbing as pole varieties) that are more suitable for single mechanized harvest as needed for processing.

Average dry yield is around 1,100 kg/ha, with an average harvest index of 0.48. For green beans, 11% of fresh weight is considered as dry matter. It takes 50 to 55 days from emergence for the crop to be ready to harvest. Flowering starts around 40 days after emergence. Maximum canopy cover occurs at the beginning of flowering, reaching a fraction of solar radiation interception of 0.95.

Table A2 - Green bean: *Baseline and future green bean planting dates for the adaptation scenarios. For future scenarios without adaptation, the planting dates are the same as for the baseline period. The planting date will be applied to each year at a location. Planting dates are determined based on a 15-day window above a base mean temperature of 15 °C.*

No.	State	County	Temperature-Based Planting Date (Day of Year)		
			Baseline	**2030sAdaptation**	**2050sAdaptation**
1	Arizona	Maricopa	44	25	15
2	California	Fresno	83	67	55
3	California	Imperial	25	13	8
4	California	Monterey	104	67	47
5	California	Yolo	87	70	60
6	Colorado	Rio Grande	160	148	138
7	Florida	Hendry	4	2	2
8	Florida	Polk	6	5	3
9	Florida	St. Johns	19	15	11
10	Georgia	Decatur	44	33	29
11	Idaho	Bingham	149	131	123
12	Idaho	Canyon	134	112	103
13	Idaho	Minidoka	148	129	120
14	Maine	Aroostook	162	147	140
15	Michigan	Montcalm	141	128	123
16	Michigan	St. Joseph	134	119	114
17	Minnesota	Dakota	135	122	116
18	Minnesota	Freeborn	136	123	119
19	Minnesota	Otter Tail	145	133	129
20	Minnesota	Renville	134	122	118
21	New York	Genesee	137	123	117
22	North Dakota	Walsh	138	128	125
23	Oregon	Marion	143	132	121
24	Oregon	Umatilla	131	118	107
25	Texas	Hidalgo	9	6	4
26	Washington	Benton	132	119	109
27	Washington	Grant	137	126	116
28	Washington	Skagit	160	141	123
29	Washington	Walla Walla	130	113	104

No.	State	County	Temperature-Based Planting Date (Day of Year)		
			Baseline	2030sAdaptation	2050sAdaptation
30	Wisconsin	Fond du Lac	138	124	119
31	Wisconsin	Langlade	151	134	130
32	Wisconsin	Portage	141	127	123

Table A3 - Green Bean: *N/P/K concentration (%) of dry matter weight (kg DM/ha) of yield and the CO_2 effects on N/P/K concentrations. The ratios of N/P/K concentrations to the dry matter of yield are assumed to be the same as soybean after Bender et al. (2015). The CO_2 effects on N/P/K concentrations are after Loladze (2014).*

Crop Component	N (%)	P (%)	K (%)	FN (%/ppm)	FP (%/ppm)	FK (%/ppm)
Yield	5.81	0.51	1.87	-0.0636	-0.0463	-0.1265

N: Nitrogen content (%) of dry matter yield
P: Phosphorus content (%) of dry matter yield
K: Potassium content (%) of dry matter yield

FN: CO_2 effects on nitrogen content of dry matter yield (%/ppm)
FP: CO_2 effects on phosphorus content of dry matter yield (%/ppm)
FK: CO_2 effects on potassium content of dry matter yield (%/ppm)

Spinach *(Spinacia oleracea)*

SPINACH-SPECIFIC PARAMETERIZATION

To establish a reference crop to be used in all 32 counties, Monterey, CA is used as the calibration point. California is the main producer in the US, with about half of the acreage and production in Monterey County. Spinach is typically sprinkler irrigated, although some processed crops in the central valley are furrow irrigated. Fresh market spinach is a short-season crop that is harvested when the crop is young. Spinach for the frozen market have a longer season although they are harvested before flowering.

Average dry yield should be around 1,400 kg/ha, with an average harvest index of 0.85. For spinach, 8.6% of fresh weight is considered as dry matter. Spinach for baby leaves clipped, teenage clipped, and bunched (fresh market) are ready to harvest 25 to 60 days after planting, while spinach for freezing are ready 70 to 120 days after planting. Spinach for baby leaves clipped, teenage clipped, and bunched (fresh market) are ready to harvest 25 to 60 days after planting, while spinach for freezing are ready 70 to 120 days after planting.

Table A2 - Spinach: *Baseline and future spinach planting dates for the adaptation scenarios. For future scenarios without adaptation, the planting dates are the same as for the baseline period. The planting date is applied to each year at a location. Planting dates are determined based on a 15-day window above a base mean temperature of 8 °C.*

No.	State	County	Temperature-Based Planting Date (Day of Year)		
			Baseline	2030sAdaptation	2050sAdaptation
1	Arizona	Maricopa	32	22	12
2	California	Fresno	32	22	12
3	California	Imperial	50	59	65
4	California	Monterey	32	22	12
5	California	Yolo	32	22	12
6	Colorado	Rio Grande	107	94	87
7	Florida	Hendry	32	22	12
8	Florida	Polk	32	22	12
9	Florida	St. Johns	32	22	12
10	Georgia	Decatur	32	22	12
11	Idaho	Bingham	96	80	71
12	Idaho	Canyon	73	57	50
13	Idaho	Minidoka	97	75	65
14	Maine	Aroostook	115	105	100
15	Michigan	Montcalm	96	87	83
16	Michigan	St. Joseph	84	79	73
17	Minnesota	Dakota	94	85	80
18	Minnesota	Freeborn	94	86	81
19	Minnesota	Otter Tail	104	95	92
20	Minnesota	Renville	95	87	82
21	New York	Genesee	92	82	77
22	North Dakota	Walsh	101	93	90
23	Oregon	Marion	55	42	37
24	Oregon	Umatilla	66	50	44
25	Texas	Hidalgo	32	22	12

No.	State	County	Temperature-Based Planting Date (Day of Year)		
			Baseline	**2030sAdaptation**	**2050sAdaptation**
26	Washington	Benton	66	51	45
27	Washington	Grant	77	63	56
28	Washington	Skagit	67	45	39
29	Washington	Walla Walla	62	49	43
30	Wisconsin	Fond du Lac	94	84	80
31	Wisconsin	Langlade	105	94	89
32	Wisconsin	Portage	96	88	84

Table A3 - Spinach: *N/P/K concentration (%) of dry matter weight (kg DM/ha) of yield and the CO_2 effects on N/P/K concentrations. The ratios of N/P/K concentrations to the dry matter of yield are after Nemadodzi et al. (2017). The CO_2 effects on N/P/K concentrations are after Loladze (2014).*

Crop Component	N (%)	P (%)	K (%)	FN (%/ppm)	FP (%/ppm)	FK (%/ppm)
Yield	4.10	0.49	5.79	-0.0473	-0.0213	-0.0060

N: Nitrogen content (%) of dry matter yield
P: Phosphorus content (%) of dry matter yield
K: Potassium content (%) of dry matter yield

FN: CO_2 effects on nitrogen content of dry matter yield (%/ppm)
FP: CO_2 effects on phosphorus content of dry matter yield (%/ppm)
FK: CO_2 effects on potassium content of dry matter yield (%/ppm)

Carrots *(Daucus carota)*

CARROT-SPECIFIC PARAMETERIZATION

California has four main production areas for carrots: the southern San Joaquin Valley and the Cuyama Valley (Kern and Santa Barbara Counties), the southern desert (Imperial and Riverside Counties), the high desert (Los Angeles County), and the central coast (Monterey County). Canopy cover relates to the capacity of the green vegetation to intercept solar radiation and should be understood as the fraction of solar radiation intercepted by the green crop canopy per unit ground. Carrot reaches a canopy cover of 0.85 in about 50 days after sowing and stays green until harvest (100-120 days after sowing).

Average processing carrot yields in CA are 33 ton/acre, equivalent to 74,154 kg/ha fresh weight. For carrots, 12.5% of fresh weight is considered as dry matter, so the average dry matter base yield is 9,269 kg dry/ha. Variety trials in CA report average yields (kg dry/ha) of 9,069 in Imperial, 9,269 in Yolo, and 6,071 in Monterey (cooler coastal area). The harvest index of carrots is about 0.65 (65% of total dry biomass produced is yield). As there is no CO_2 response in the literature for carrots, the CO_2 effect used for tomatoes is also used for carrots.

Table A2 - Carrots: *Baseline and future carrot planting dates for the adaptation scenarios. For future scenarios without adaptation, the planting dates are the same as for the baseline period. The planting date will be applied to each year at a location. Planting dates are determined based on a 15-day window above a base mean temperature of 8 °C.*

No.	State	County	Temperature-Based Planting Date (Day of Year)		
			Baseline	2030sAdaptation	2050sAdaptation
1	Arizona	Maricopa	2	357	347
2	California	Fresno	32	22	12
3	California	Imperial	2	357	347
4	California	Monterey	32	22	12
5	California	Yolo	32	22	12
6	Colorado	Rio Grande	107	94	87
7	Florida	Hendry	2	357	347
8	Florida	Polk	2	357	347
9	Florida	St. Johns	2	357	347
10	Georgia	Decatur	2	357	347
11	Idaho	Bingham	96	80	71
12	Idaho	Canyon	73	57	50
13	Idaho	Minidoka	97	75	65
14	Maine	Aroostook	115	105	100
15	Michigan	Montcalm	96	87	83
16	Michigan	St. Joseph	84	79	73
17	Minnesota	Dakota	94	85	80
18	Minnesota	Freeborn	94	86	81
19	Minnesota	Otter Tail	104	95	92
20	Minnesota	Renville	95	87	82
21	New York	Genesee	92	82	77
22	North Dakota	Walsh	101	93	90
23	Oregon	Marion	55	42	37
24	Oregon	Umatilla	66	50	44
25	Texas	Hidalgo	2	357	347

No.	State	County	Temperature-Based Planting Date (Day of Year)		
			Baseline	2030sAdaptation	2050sAdaptation
26	Washington	Benton	66	51	45
27	Washington	Grant	77	63	56
28	Washington	Skagit	67	45	39
29	Washington	Walla Walla	62	49	43
30	Wisconsin	Fond du Lac	94	84	80
31	Wisconsin	Langlade	105	94	89
32	Wisconsin	Portage	96	88	84

Table A3 - Carrot: *N/P/K concentration (%) of dry matter weight (kg DM/ha) of yield and the CO_2 effects on N/P/K concentrations. The N concentrations dry matter of yield are from Prasad et al. (2015). The P and K concentrations are estimated by a nutrient concentration ratio of N to P and K after Gugala et al. (2015) and HAIFA (*https://www.haifa-group.com/crop-guide/field-crops/crop-guide-potato/nutrients-growing-potatoes*). The CO_2 effects on N/P/K concentrations are after Loladze (2014).*

Crop Component	N (%)	P (%)	K (%)	FN (%/ppm)	FP (%/ppm)	FK (%/ppm)
Yield	1.70	0.17	2.55	-0.01592	-0.01095	-0.01095

N: Nitrogen content (%) of dry matter yield
P: Phosphorus content (%) of dry matter yield
K: Potassium content (%) of dry matter yield

FN: CO_2 effects on nitrogen content of dry matter yield (%/ppm)
FP: CO_2 effects on phosphorus content of dry matter yield (%/ppm)
FK: CO_2 effects on potassium content of dry matter yield (%/ppm)

Strawberry *(Fragaria × ananassa)*

STRAWBERRY-SPECIFIC PARAMETERIZATION

Strawberries are perennials and can be grown for multiple years, but commercially, they are typically grown for a single season. Commercial varieties are propagated from "daughter plants" genetically identical to "mother plants," which are used for transplanting. Fall/Winter planting is used for plants that produce in the spring and summer. Strawberries grow better in maritime and Mediterranean areas of central and southern California (warm winters, and relatively cool and dry summers). The base temperature is relatively low, around 3 °C. RUE fluctuates between 1.2 and 1.5 g MJ^{-1} m^{-2}, and SIMPLE used 1.3 g MJ^{-1} m^{-2}. Leaf area index develops from near zero after transplant to 1.5 to 2.2 by the end of the season (Fall/Winter planting) in Florida, and up to 3 in California.

California current fresh yields are 650-700 cwt/acre (72,865 to 78,470 kg/ha). For strawberry, 9% of fresh weight is considered as dry matter, so current dry yields in California are 6,557 to 7,062 kg/ha. Harvest index is highly variable (0.2-0.8) depending on variety and when the crop is ended. The harvest index is suggested as 0.8 in Imperial, California, which has the highest thermal times accumulation during planting and harvest. The harvest index in other locations depend on their individual thermal times accumulated.

Table A2 - Strawberry: *Baseline strawberry planting and harvesting dates. For future scenarios without adaptation, the planting dates are the same as for the baseline period. The planting date will be applied to each year at a location. Planting and harvesting dates are based on USDA recommended dates (https://strawberryplants.org/strawberry-planting-guide/). For adaptation, one-week earlier planting for 2030s and two weeks for 2050s are used.*

No.	State	County	Planting (DOY)	Harvesting (DOY)	Season Length (days)
1	Arizona	Maricopa	15	166	151
2	California	Fresno	15	166	151
3	California	Imperial	15	166	151
4	California	Monterey	15	166	151
5	California	Yolo	15	166	151
6	Colorado	Rio Grande	110	200	90
7	Florida	Hendry	288	80	157
8	Florida	Polk	288	80	157
9	Florida	St. Johns	288	80	157
10	Georgia	Decatur	304	96	157
11	Idaho	Bingham	110	200	90
12	Idaho	Canyon	90	180	90
13	Idaho	Minidoka	110	200	90
14	Maine	Aroostook	130	220	90
15	Michigan	Montcalm	115	205	90
16	Michigan	St. Joseph	90	180	90
17	Minnesota	Dakota	130	220	90
18	Minnesota	Freeborn	130	220	90
19	Minnesota	Otter Tail	130	220	90
20	Minnesota	Renville	130	220	90
21	New York	Genesee	90	190	100
22	North Dakota	Walsh	130	220	90
23	Oregon	Marion	60	180	120
24	Oregon	Umatilla	90	210	120
25	Texas	Hidalgo	15	150	135

No.	State	County	Planting (DOY)	Harvesting (DOY)	Season Length (days)
26	Washington	Benton	90	210	120
27	Washington	Grant	90	210	120
28	Washington	Skagit	75	195	120
29	Washington	Walla Walla	90	210	120
30	Wisconsin	Fond du Lac	120	210	90
31	Wisconsin	Langlade	130	220	90
32	Wisconsin	Portage	130	220	90

Table A3 - Strawberry: *N/P/K concentration (%) of dry matter weight (kg DM/ha) of yield and the CO_2 effects on N/P/K concentrations. The N/P/K concentrations dry matter of yield are after Villalobos et al. (2020). The CO_2 effects on N/P/K concentrations are after Loladze (2014).*

Crop Component	N (%)	P (%)	K (%)	FN (%/ppm)	FP (%/ppm)	FK (%/ppm)
Yield	1.35	0.23	1.95	-0.01699	-0.014	-0.01615

N: Nitrogen content (%) of dry matter yield
P: Phosphorus content (%) of dry matter yield
K: Potassium content (%) of dry matter yield

FN: CO_2 effects on nitrogen content of dry matter yield (%/ppm)
FP: CO_2 effects on phosphorus content of dry matter yield (%/ppm)
FK: CO_2 effects on potassium content of dry matter yield (%/ppm)

Orange *(Citrus × sinensis)*

ORANGE-SPECIFIC PARAMETERIZATION

Orange trees are evergreen plants but, unlike many lime and lemon trees, do not produce fruit continually throughout the year. Each tree produces one crop of fruit per year, with the fruiting cycle taking up to 10-12 months for some varieties. Typically, orange trees reach full canopy cover (~0.9) after 5 years since planting, and the annual production will remain stable (Roka et al. 1997). Oranges have traditionally been harvested in winter, but new varieties now allow for harvest almost all year. Generally, early-season varieties are ready for harvest between October and January, mid-season between December and February, and late-season between March and June.

Oranges can be grown in a variety of arid and humid climates and can withstand temperatures ranging from -2 to 40 °C. The base temperature is relatively high, around 10-12 °C. No heat stress before 42 °C. RUE is relatively low, e.g., SIMPLE uses 0.7 g MJ^{-1} m^{-2}, close to bananas (0.8 g MJ^{-1} m^{-2}). Leaf area index will remain relatively stable when it reaches the full canopy cover after 5 years. Maximum Leaf area index is about 3.5, about 0.9 of canopy cover. The orange harvest index is relatively low, ranging between 0.1 to 0.3 depending on cultivars. A harvest index of 0.15 for Valencia is suggested for modeling.

Florida and California are the two major orange growing states in the United States of America. In 2019, Florida accounted for 59% of total US orange production, California 40%, and Texas and Arizona the remaining 1% (*Citrus Fruit Summary 2019:* https://ccqc.org/wp-content/uploads/USDA-Citrus-Fruits-Summary-82620.pdf). Orange fresh yield in FL and CA can reach 300-400 box/acre. Aa box is defined as containing 40.8 kg of fruits (https://orangebook.tetrapak.com/chapter/fruit-processing). The fresh yield is from 30,233 to 40,210 kg/ha. For oranges, ~12% of fresh weight is considered as dry matter, so the dry matter yield ranges from 3,628 to 4,825 kg/ha.

Table A2 - Orange: *Baseline and future orange planting and harvesting dates. Simulations were applied in Florida, California, Texas, and Arizona where oranges are grown currently. Cultivar of Valencia was used in the simulations. Planting date (bud burst) was set on June 1 and harvesting date was set on May 31 for both baseline and future. No adaptations were applied for the 2030s and 2050s.*

No.	State	County	Planting (DOY)	Harvesting (DOY)	Season Length (days)
1	Arizona	Maricopa	151	150	365
2	California	Fresno	151	150	365
3	California	Imperial	151	150	365
4	California	Monterey	151	150	365
5	California	Yolo	151	150	365
6	Colorado	Rio Grande			
7	Florida	Hendry	151	150	365
8	Florida	Polk	151	150	365
9	Florida	St. Johns	151	150	365
10	Georgia	Decatur			
11	Idaho	Bingham			
12	Idaho	Canyon			
13	Idaho	Minidoka			
14	Maine	Aroostook			
15	Michigan	Montcalm			
16	Michigan	St. Joseph			
17	Minnesota	Dakota			
18	Minnesota	Freeborn			
19	Minnesota	Otter Tail			
20	Minnesota	Renville			
21	New York	Genesee			
22	North Dakota	Walsh			

No.	State	County	Planting (DOY)	Harvesting (DOY)	Season Length (days)
23	Oregon	Marion			
24	Oregon	Umatilla			
25	Texas	Hidalgo	151	150	365
26	Washington	Benton			
27	Washington	Grant			
28	Washington	Skagit			
29	Washington	Walla Walla			
30	Wisconsin	Fond du Lac			
31	Wisconsin	Langlade			
32	Wisconsin	Portage			

Table A3 - Orange: *N/P/K concentration (%) of dry matter weight (kg DM/ha) of yield, and the CO_2 effects on N/P/K concentrations. The N//P/K concentrations dry matter of yield are after Villalobos et al. (2020). The CO_2 effects on N/P/K concentrations are after Loladze (2014).*

Crop Component	N (%)	P (%)	K (%)	FN (%/ppm)	FP (%/ppm)	FK (%/ppm)
Yield	1.20	0.14	1.35	-0.0351	0	-0.0113

N: Nitrogen content (%) of dry matter yield
P: Phosphorus content (%) of dry matter yield
K: Potassium content (%) of dry matter yield

FN: CO_2 effects on nitrogen content of dry matter yield (%/ppm)
FP: CO_2 effects on phosphorus content of dry matter yield (%/ppm)
FK: CO_2 effects on potassium content of dry matter yield (%/ppm)