Assessing Local Vulnerability to Climate Change in Agriculture for Tocantins, Brazil/*

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Introduction

This research develops a methodology of indicators for assessing local vulnerability to climate change in agricultural systems. Such indicators can better inform local planning, investment decisions and the risk management in the view of a changing environment. In particular, project investments can greatly be benefited by the availability of local vulnerability indicators that can capture their potential risks.

Systems are represented by municipalities, which are the closest geographical representation of agricultural systems where agronomical processes and climatic variables interact within. Our main methodological contribution is the development of vulnerability indicators that allow policy makers identifying main vulnerability drivers and designing climate change adaptation policies at the local level. Once vulnerability and adaptation assessments are computed, the degree of resiliency of local systems can be obtained to inform policy.

Objectives

The objective is the application of this methodology for the municipalities of the State of Tocantins, one of the Brazil's agricultural frontier regions, where the Development Program for the Southwest (PRODOESTE), an Interamerican Development Bank investment project is currently operating.

Methods

The proposed indicator of local vulnerability to climate change in agriculture allows assessing within the system the main components of vulnerability at a local level: stressors exposure (SE), stressors sensitivity (SS) and adaptive capacity (AC). This indicator combines the methodology of Luers et al.(2003) (2003) and the estimates a fixed effects model by crop to estimate a sensitivity indicator at the county-level to assess how climate stressors (Average Temperature, Tem_{ijt} and Accumulated Precipitation, $Prec_{ijt}$) influence systems' yields (Y_{ijt}) by growing stage using information on geographical, socioeconomic and temporal characteristics of local systems. F_i and F_j are time invariant variables at the county-level and crop-level respectively. A trend and year fixed effects (t) control for state changes over time such as technological progress (i.e. introduction of new seed varieties).

$$Y_{ijt} = \sum_{g=1}^{4}\left[\alpha_{1g}Prec_{ijtg} + \alpha_{2g}Temp_{ijtg}\right] + \gamma'F_i + \eta'F_j + t + trend + \varepsilon_{ijt} \qquad (4)$$

Exposure Indicator *(E)*

It is a frequency measure of climate adverse events for the crop development at municipality level.

Exposure $(E) = Pr_S dS$

Sensitivity Indicator *(SS)*

The SS captures the system response to changes in stressors where $\partial Yield/_{\partial S}$ is the estimated response of yields to stressor S, $Yield$ is the observed crop yield in a given system (county) and $Yield_{threshold}$ represents the point of reference for a given system below which the agricultural system becomes "damaged".

$$SS = f\left(\frac{Sensitivity}{Distance\ to\ Threshold}\right) = f\left(\frac{\partial Yield/_{\partial S}}{Yield/_{Yield_{threshold}}}\right)$$

Vulnerability Indicator *(V)*

Vulnerability measure is defined as the expected value of the system's sensitivity given a threshold of damage, where Pr_S refers to the density function of stressor S.

$$V = Expected\ Value[SS] = \int\left(\frac{\partial Yield/_{\partial S}}{Yield/_{Yield_{threshold}}}\right)Pr_S dS$$

Adaptive Capacity Indicator *(AC)*

$$AC = V(ec) - V(mc)$$

This indicator reflects the magnitude to which a system can be modified (mc) to become less vulnerable than under the existing conditions (ec).

The flexibility of these indicators allows ranking systems with different yield performance, different exposure to climate risk and different levels of sensibility. Thus, even when two systems show the same level of exposure, their vulnerability indicators can differ depending on yield performance and sensitivity.

Results

PRODOESTE covers 14 of the 139 municipalities of the State of Tocantins. In its first stage, PRODOESTE will provide irrigation for 7,100 hectares located in the Pium and Riozinho river basins and benefiting mainly rice, soybeans, corn, watermelon and beans producers.

Figure 1. State of Tocantins and Municipalities with PRODOESTE

In most of Tocantins areas, growing season is largely determined by occurrence of the rainy and dry seasons of the region (May to September). So, drought risks and temperature increments can have significant effect on water balance because of the potential evapotranspiration. Potential harm from drought depends on its duration and the type of species and genotypes/cultivar affected.

Baseline Assessment

Local vulnerability indicators are estimated using historical records that allow assessing all components of vulnerability for the local systems.

Table 1. Exposure Indicators, Baseline Assessment

Municipalities	Exposure index* Temperature	Exposure index* Precipitation
1. Aliança do Tocantins	0.167 M	0.396 H
2. Alvorada	0.021 L	0.479 H
3. Araguaçu	0.021 L	0.479 H
4. Cariri do Tocantins	0.021 L	0.438 H
5. Cristalândia (1ª Etapa)	0.229 H	0.375 M
6. Crixás do Tocantins	0.187 M	0.375 M
7. Dueré	0.187 M	0.417 H
8. Figueirópolis	0.021 L	0.479 H
9. Formoso do Araguaia	0.229 H	0.438 H
10. Lagoa da Confusão (1ª Etapa)	0.250 H	0.438 H
11. Pium (1ª Etapa)	0.271 H	0.375 M
12. Sandolândia	0.083 M	0.438 H
13. Santa Rita do Tocantins	0.229 H	0.396 H
14. Talismã	0.021 L	0.375 M
PRODOESTE Average Municipality	0.138 M	0.424 H
Tocantins Average Municipalities**	0.128 M	0.348 M

*Frequency indicator. L stands for low exposure, M stands for medium exposure and H stands for high exposure.
**PRODOESTE municipalities are not considered in this calculus.

Table 2. Sensitivity Indicators by Crop and Aggregate, Baseline Assessment

Municipalities	Soybeans	Rice	Corn	Watermelon	Beans	Aggregate
	Sensitivity to Precipitation					
1. Aliança do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2. Alvorada	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3. Araguaçu	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
4. Cariri do Tocantins		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5. Cristalândia (1ª Etapa)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6. Crixás do Tocantins	[illegible]	[illegible]	[illegible]			[illegible]
7. Dueré	[illegible]	[illegible]	[illegible]			[illegible]
8. Figueirópolis	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
9. Formoso do Araguaia	[illegible]	[illegible]	[illegible]			[illegible]
10. Lagoa da Confusão (1ª Etapa)		[illegible]	[illegible]		[illegible]	[illegible]
11. Pium (1ª Etapa)	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
12. Sandolândia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13. Santa Rita do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14. Talismã		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PRODOESTE Average	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tocantins Average *	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Municipalities	Soybeans	Rice	Corn	Watermelon	Beans	Aggregate
	Sensitivity to Temperature					
1. Aliança do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2. Alvorada	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3. Araguaçu	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
4. Cariri do Tocantins		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5. Cristalândia (1ª Etapa)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6. Crixás do Tocantins	[illegible]	[illegible]	[illegible]			[illegible]
7. Dueré	[illegible]	[illegible]	[illegible]			[illegible]
8. Figueirópolis	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
9. Formoso do Araguaia	[illegible]	[illegible]	[illegible]			[illegible]
10. Lagoa da Confusão (1ª Etapa)		[illegible]	[illegible]		[illegible]	[illegible]
11. Pium (1ª Etapa)	[illegible]	[illegible]	[illegible]		[illegible]	[illegible]
12. Sandolândia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13. Santa Rita do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14. Talismã		[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PRODOESTE Average	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tocantins Average *	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

/* This aggregation does not include municipalities where PRODOESTE is operating.

Sensitivity indicator show how much increases the sensitivity of yield (tons per hectare) respect to the threshold of damage as a result of one additional Celsius degree in temperature or a reduction of one millimeter of precipitation per day.

Table 3. Local Vulnerability Indicators in Agriculture Systems, Baseline Assessment

Municipalities	Soybeans	Rice	Corn	Watermelon	Beans	Aggregate
	Vulnerability to Precipitation					
1. Aliança do Tocantins	0.0245	0.0113	0.0073			0.0031
2. Alvorada	0.0151	0.0015	0.0040	0.0070	0.0012	0.0030
3. Araguaçu	0.0388	0.0038	0.0036	0.0005		0.0038
4. Cariri do Tocantins	0.0160	0.0026	0.0040	0.0017	0.0045	0.0039
5. Cristalândia (1ª Etapa)	0.0306	0.0020	0.0037	0.0071	0.0030	0.0113
6. Crixás do Tocantins	0.0306	0.0029	0.0049	0.0076	0.0036	0.0039
7. Dueré	0.0151	0.0010	0.0016	0.0078	0.0024	0.0035
8. Figueirópolis	0.0307	0.0013	0.0071	0.0005	0.0037	0.0028
9. Formoso do Araguaia	0.0848	0.0015	0.0076	0.0036	0.0015	0.0048
10. Lagoa da Confusão (1ª Etapa)	0.0215	0.0002	0.0035	0.0033	0.0030	0.0032
11. Pium (1ª Etapa)	0.0215	0.0006	0.0050	0.0018	0.0025	0.0042
12. Sandolândia	0.0692	0.0074	0.0094			0.0044
13. Santa Rita do Tocantins	0.0290	0.0035	0.0012			0.0088
14. Talismã	0.0793	0.0028	0.0040		0.0047	0.0053
PRODOESTE Average	0.0252	0.0018	0.0079	0.0036	0.0029	0.0084
Tocantins Average *	0.0042	0.0012	0.0079	0.0030	0.0031	0.0085

Municipalities	Soybeans	Rice	Corn	Watermelon	Beans	Aggregate
	Vulnerability to Temperature					
1. Aliança do Tocantins	0.5162	0.2361	0.3906			0.4021
2. Alvorada	[illegible]	[illegible]	0.1486	[illegible]	[illegible]	0.0654
3. Araguaçu	0.0773	0.0805	0.0572	0.0772		0.0675
4. Cariri do Tocantins	[illegible]	0.0868	[illegible]	[illegible]	0.0610	0.0702
5. Cristalândia (1ª Etapa)	0.5061	0.2155	0.3294	0.1718	0.3354	0.2722
6. Crixás do Tocantins	0.4703	0.2297	0.3482	0.1781	0.3643	0.3729
7. Dueré	0.4344	0.1460	0.3455	0.1463	0.3147	0.2477
8. Figueirópolis	0.0653	0.0811	0.0470	0.0360	0.0519	0.0599
9. Formoso do Araguaia	0.4136	0.1388	0.3443	0.1347	0.3586	0.2477
10. Lagoa da Confusão (1ª Etapa)	0.5769	0.1760	0.2582	0.1450	0.3374	0.2274
11. Pium (1ª Etapa)	0.4063	0.1380	0.3399	0.1508	0.3361	0.3057
12. Sandolândia	0.2784	0.1250	0.1968			0.1748
13. Santa Rita do Tocantins	0.6343	0.3119	0.4364			0.4235
14. Talismã	[illegible]	0.0434	0.1444		0.0651	0.0654
PRODOESTE Average	0.3201	0.1188	0.3265	0.0910	0.1629	0.2143
Tocantins Average *	0.2407	0.1724	0.2520	0.1474	0.2278	0.2738

/* This aggregation does not include municipalities where PRODOESTE is operating.

Local vulnerability is notably higher in soybeans production for both stressors, in contrast with watermelon production. Santa Rita do Tocantins and Aliança do Tocantins show the highest temperature vulnerability.

Figure 2. Precipitation vulnerability indicators for Tocantins and PRODOESTE's municipalities

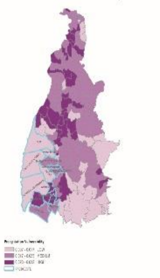
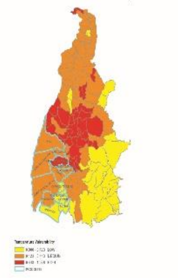


Figure 2. Precipitation vulnerability indicators for Tocantins and PRODOESTE's municipalities



Climate Change Assessment

For the construction of the components of the vulnerability indicators under climate change scenarios, we replaced historical data with climate change scenarios data and the econometric model was re-estimated for four scenarios (A1F1, A2, B1, B2) and two horizons (medium-term and long-term).

Table 4. Aggregate sensitivity indicators for agricultural systems by climate change scenario

Municipalities	Baseline	Medium Term Scenarios				Long Term Scenarios			
	Precipitation								
		B1	A2	B2	A1F1	B1	A2	B2	A1F1
1. Aliança do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2. Alvorada	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3. Araguaçu	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4. Cariri do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5. Cristalândia (1ª Etapa)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6. Crixás do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7. Dueré	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8. Figueirópolis	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9. Formoso do Araguaia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10. Lagoa da Confusão (1ª Etapa)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
11. Pium (1ª Etapa)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12. Sandolândia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13. Santa Rita do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14. Talismã	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PRODOESTE Average	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tocantins Average *	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

Municipalities	Baseline	Medium Term Scenarios				Long Term Scenarios			
	Temperature								
		B1	A2	B2	A1F1	B1	A2	B2	A1F1
1. Aliança do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
2. Alvorada	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
3. Araguaçu	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
4. Cariri do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
5. Cristalândia (1ª Etapa)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
6. Crixás do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
7. Dueré	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
8. Figueirópolis	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
9. Formoso do Araguaia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
10. Lagoa da Confusão (1ª Etapa)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
11. Pium (1ª Etapa)	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
12. Sandolândia	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13. Santa Rita do Tocantins	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14. Talismã	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
PRODOESTE Average	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
Tocantins Average *	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

/* This aggregation does not include municipalities where PRODOESTE is operating.

The sensitivity indicator increases with more extreme scenarios (A1F1). Long-term A1F1 scenarios are two-fold higher than A1F1 medium-term scenarios. In general terms, Alvorada, Cariri do Tocantins and Talismã show the highest levels of vulnerability as a result of climate change.

Table 5. Local vulnerability to climate change indicators for agricultural systems

Municipalities	Baseline	Medium Term Scenarios				Long Term Scenarios			
	Precipitation								
		B1	A2	B2	A1F1	B1	A2	B2	A1F1
1. Aliança do Tocantins	0.0268	0.0281	0.0285	0.0292	0.0293	0.0357	0.0470	0.0394	0.0540
2. Alvorada	0.0125	0.0133	0.0133	0.0136	0.0138	0.0167	0.0216	0.0179	0.0244
3. Araguaçu	0.0213	0.0224	0.0225	0.0230	0.0232	0.0283	0.0371	0.0302	0.0430
4. Cariri do Tocantins	0.0164	0.0173	0.0175	0.0179	0.0180	0.0219	0.0292	0.0241	0.0332
5. Cristalândia (1ª Etapa)	0.0214	0.0226	0.0227	0.0231	0.0235	0.0285	0.0368	0.0305	0.0417
6. Crixás do Tocantins	0.0152	0.0162	0.0152	0.0155	0.0170	0.0206	0.0267	0.0219	0.0308
7. Dueré	0.0147	0.0155	0.0155	0.0158	0.0162	0.0195	0.0257	0.0209	0.0257
8. Figueirópolis	0.0163	0.0175	0.0175	0.0178	0.0181	0.0221	0.0286	0.0236	0.0322
9. Formoso do Araguaia	0.0293	0.0310	0.0313	0.0319	0.0326	0.0392	0.0516	0.0425	0.0603
10. Lagoa da Confusão (1ª Etapa)	0.0127	0.0133	0.0135	0.0139	0.0138	0.0170	0.0227	0.0188	0.0257
11. Pium (1ª Etapa)	0.0201	0.0212	0.0217	0.0218	0.0223	0.0270	0.0359	0.0294	0.0419
12. Sandolândia	0.0202	0.0212	0.0215	0.0220	0.0223	0.0271	0.0367	0.0300	0.0426
13. Santa Rita do Tocantins	0.0187	0.0197	0.0200	0.0205	0.0207	0.0254	0.0347	0.0284	0.0404
14. Talismã	0.0196	0.0203	0.0211	0.0217	0.0219	0.0268	0.0366	0.0296	0.0424
PRODOESTE Average	0.0190	0.0200	0.0202	0.0206	0.0209	0.0254	0.0337	0.0277	0.0367
Tocantins Average *	0.0184	0.0194	0.0196	0.0200	0.0203	0.0247	0.0329	0.0270	0.0380
	Temperature								
	Baseline	Medium Term Scenarios				Long Term Scenarios			
		B1	A2	B2	A1F1	B1	A2	B2	A1F1
1. Aliança do Tocantins	0.6885	0.7331	0.7321	0.7518	0.7530	0.9174	1.2231	1.0141	1.3956
2. Alvorada	0.2789	0.2944	0.2955	0.3008	0.3064	0.3706	0.4802	0.3975	0.5426
3. Araguaçu	0.0658	0.0692	0.0697	0.0710	0.0726	0.0873	0.1146	0.0943	0.1329
4. Cariri do Tocantins	0.1977	0.2080	0.2106	0.2158	0.2165	0.2641	0.3520	0.2908	0.3954
5. Cristalândia (1ª Etapa)	0.5067	0.5242	0.5246	0.5307	0.5368	0.4081	0.5262	0.4560	0.9370
6. Crixás do Tocantins	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7. Dueré	0.0617	0.0651	0.0655	0.0665	0.0679	0.0820	0.1068	0.0881	0.1205
8. Figueirópolis	0.0634	0.0673	0.0679	0.0692	0.0703	0.0858	0.1110	0.0918	0.1251
9. Formoso do Araguaia	0.8175	0.8644	0.8721	0.8831	0.9081	1.0907	1.4446	1.1848	1.6817
10. Lagoa da Confusão (1ª Etapa)	0.1752	0.1842	0.1864	0.1915	0.1919	0.2346	0.3135	0.2594	0.3551
11. Pium (1ª Etapa)	0.7351	0.7652	0.7750	0.7835	0.8040	0.9741	1.2969	1.0603	1.5171
12. Sandolândia	0.6248	0.6657	0.6646	0.6806	0.6894	0.8400	1.1370	0.9279	1.3212
13. Santa Rita do Tocantins	0.1780	0.1867	0.1896	0.1950	0.1966	0.2408	0.3297	0.2693	0.3838
14. Talismã	0.1924	0.2021	0.2063	0.2112	0.2126	0.2593	0.3551	0.2904	0.4131
PRODOESTE Average	0.3133	0.3293	0.3326	0.3400	0.3447	0.4184	0.5565	0.4575	0.6409
Tocantins Average *	0.2647	0.2774	0.2802	0.2862	0.2910	0.3581	0.4708	0.3857	0.5459

/* This aggregation does not include municipalities where PRODOESTE is operating.

Long-term scenarios seem particularly risky in terms of temperature vulnerability. Municipalities such as Araguacú and Dueré show low vulnerability levels across all scenarios. In contrast, municipalities such as Alianza do Tocantins, Formoso do Araguaia and Pium remain as the most vulnerable across climate change scenarios.

Figure 4. Differences in precipitation vulnerability in the medium-term:Baseline-A1F1 climate change scenario

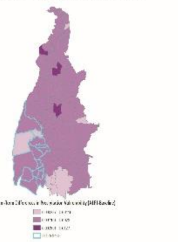
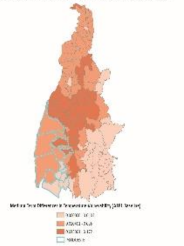


Figure 5. Differences in temperature vulnerability in the medium-term:Baseline-A1F1 climate change scenario



Adaptive Capacity Assessment

Results are consistent within scenarios; adaptive capacity (vulnerability reduction) based on an irrigation strategy is more effective for cope with more extreme scenarios (A1F1). In general terms, our model predicts that adaptive capacity will be higher for more extreme scenarios of climate change.

Table 6. Adaptive Capacity Assessment Based on Irrigation Conditions, Climate Change Assessment

Variable	Horizon	Scenario	Mean	Std. Dev.	Min	Max
Precipitation	Medium-Term	A1F1	[illegible]	[illegible]	[illegible]	[illegible]
		A2	[illegible]	[illegible]	[illegible]	[illegible]
		B1	[illegible]	[illegible]	[illegible]	[illegible]
		B2	[illegible]	[illegible]	[illegible]	[illegible]
	Long-Term	A1F1	[illegible]	[illegible]	[illegible]	[illegible]
		A2	[illegible]	[illegible]	[illegible]	[illegible]
		B1	[illegible]	[illegible]	[illegible]	[illegible]
		B2	[illegible]	[illegible]	[illegible]	[illegible]

Variable	Horizon	Scenario	Mean	Std. Dev.	Min	Max
Temperature	Medium Term	A1F1	[illegible]	[illegible]	[illegible]	[illegible]
		A2	[illegible]	[illegible]	[illegible]	[illegible]
		B1	[illegible]	[illegible]	[illegible]	[illegible]
		B2	[illegible]	[illegible]	[illegible]	[illegible]
	Long-Term	A1F1	[illegible]	[illegible]	[illegible]	[illegible]
		A2	[illegible]	[illegible]	[illegible]	[illegible]
		B1	[illegible]	[illegible]	[illegible]	[illegible]
		B2	[illegible]	[illegible]	[illegible]	[illegible]

Conclusions

PRODOESTE municipalities show a medium level of local vulnerability to climate change in Agriculture. Adaptation strategies such as irrigation investment can potentially counteract vulnerability of these local systems to climate change.

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Assessing Local Vulnerability to Climate Change in Agriculture: An Application to the State of Tocantins, Brazil

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This research develops several indicators for assessing local vulnerability to climate change in the agricultural sector of Tocantins, Brazil, where the Inter-American Development Bank is carrying irrigation investments via the Development Program for the Southwest (PRODOESTE). Vulnerability to climate indicators are constructed from exposure and sensitivity indicators and estimated using panel data on yields and farmers' profits as a function of climatic variables. Our baseline assessment indicates that those municipalities where PRODOESTE operates present medium to high levels of precipitation and temperature vulnerability, relative to the rest of Tocantins. In particular, temperature vulnerability is higher than precipitation vulnerability. We also find that vulnerability will increase in all municipalities due to climate change and it will be higher in the long-run and in more extreme climate change scenarios. Finally, irrigation is evaluated as a potential adaptation strategy and it is found to reduce climate vulnerability in the long-term, indicating that PRODOESTE's irrigation investments may be successful at reducing vulnerability due to climate change.

JEL classification: *Q1, Q51, Q54.*

Key words: *Local Vulnerability in Agriculture, Climate Change, Irrigation Projects.*

1. Introduction

The consensus establishes that the effects of a warmer planet as a result of climate change will be overwhelmingly negative on mostly every sphere of human existence: electricity and water, safety, health, food accessibility, among others. Climate change will potentially have distributional effects associated with reallocations of natural resources (water, fauna and flora). Vulnerability encompasses a wide variety of concepts including exposure, sensitivity or susceptibility to harm and lack of capacity to cope with climate change, as well as adaptation capacity (IPCC, 2014). Differences in climate vulnerability and exposure arise from non-climatic factors and from multidimensional inequalities often produced by uneven development processes, which induce differential risks from climate change (IPCC, 2014).[1]

In the agricultural sector, it is projected that climate change could have long-term impacts. However, public and private investments, irrigation, new crop varieties, cropping systems and agricultural management strategies could be implemented by farmers to counterweight climate change in those systems that could result more affected. In this context, the development of local vulnerability indicators can support the execution of more informed decisions and better manage risks associated with climate variability. In particular, project investments can be greatly benefited by the availability of vulnerability indicators at the local level that can capture their potential risks.

Thus, the purpose of vulnerability indicators at the system level is to better capture risks associated with climate. An effective indicator of local vulnerability includes the assessment of all its elements: exposure, sensitivity, vulnerability and adaptation (the capacity to build resilience). Those components should be comparable across systems and be able to capture systemic dynamics.

Several challenges emerge when evaluating vulnerability of investment projects and possible adaptation strategies to reduce those vulnerabilities. The first challenge is to assess vulnerability since it is a complex concept that involves physical and social interactions. A second challenge is to identify and to evaluate the multiple causal structures and processes that prompt vulnerability

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[1] The system or local dimension comprises a set of interdependent components forming an integrated entity that is delineated by its spatial and temporal boundaries (IPCC, 2014).

at the local and regional levels. Finally, a third challenge is to identify successful policy interventions to reduce vulnerability.

Existing indices of vulnerability to climate change show conceptual, methodological and empirical weaknesses that hamper the robustness, transparency and policy relevance of such indicators (Füssel, 2009).[2] Vulnerability indicators at the national level are limited since they fail to accurately rank and assess vulnerability at the local level. Although some authors have studied the effects of climate change on farms and stockbreeders for Brazil (Carriquiry, 2012; Romero and Mendoza, 2012), to our knowledge no method is able to rank the units of observation according to their local vulnerability.

In particular, for local investment projects a more reliable indicator should be estimated at the local level and should reflect the three dimensions aforementioned: stressors sensitivity (SS), stressors exposure (SE) and adaptive capacity (AC) of the evaluated system (IPCC, 2007).

In this article we propose calculating vulnerability and adaptation using the metrics introduced by Luers et al. (2003). These metrics represent the four main components that determine vulnerability of systems: exposure, sensitivity, vulnerability and adaptive capacity to stressors. The main contribution of this work relies on the construction and the analysis of such indicators to inform policy using information on geographical, socioeconomic and temporal characteristics of local systems, so that policy makers can identify main vulnerability drivers and design climate change adaptation policies at the local level. Once these vulnerability and adaptation assessments are computed, the degree of resiliency of local systems is obtained to inform policy.

We show how to derive vulnerability indicators and adaptation assessments for the Inter-American Development Bank's agricultural project: The Development Program for the Southwest region of the State of Tocantins (PRODOESTE) (BR-L1152) in Brazil. Our baseline assessment indicates that those municipalities where PRODOESTE operates present medium to high levels of precipitation and temperature vulnerability, relative to the rest of Tocantins. Climate change will increase both precipitation and temperature vulnerability. Additionally, irrigation in those

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[2] Usually, indicators of vulnerability are used to monitor trends and explore conceptual frameworks; vulnerability indices are limited in their application due to the lack of a rigorous method to select variables and because their relative weights are highly sensitive to data aggregation and availability (Füssel, 2009).

municipalities is found to be able to reduce vulnerability, especially temperature vulnerabilities, which are the mores extreme ones.

2. *Assessing local vulnerability in the agricultural sector*

We assess the main four components for the local vulnerability of the system to climatic stressors using the metrics developed by Luers et al. (2003). The method is based on a data intensive econometric analysis that can be applied to any country with good quality information on climate, crop yields and sociodemographic variables.

In this article, counties or municipalities are used as the systems to be evaluated and crop yields are the outcome variable used to evaluate climate change vulnerability within systems because two reasons: data availability and as yields reflect productivity and farm income. Thus, we assess the relationship between crop yields and their climatic stressors (precipitation and temperature) at a local level, controlling for socioeconomic and other variables that could shape the relationship (outcome variable vs stressors) and the effectiveness of adaptation strategies.

The first component is the local exposure indicator that reflects, at the system level, the varying magnitudes and frequencies of stressors' realizations (climate realizations). Once the system, growing season stages and stressors have been defined, we construct an exposure indicator at the municipality level (system) based on the available historical climate data. For every growing season stage, it is defined an exposure indicator based on the number of times historical temperature and precipitation during each stage of the growing season felt outside a given range, appropriate for crop development. More formally, exposure is defined as a probability density function of the stressor (precipitation or temperature):

$$Exposure(E) = Pr_S dS \tag{1}$$

The second component is the sensitivity (SS) indicator that captures the systems' response to climate stressors (precipitation and average temperature) weighted by the rate of estimated yields to the threshold below which the agricultural system is considered as damaged. The primary response of agricultural systems to stressors is obtained from the marginal impacts of stressors across four stages of the growing season on crop yields:

$$SS = f\left(\frac{Sensitivity}{Distance\ to\ Threshold}\right) = f\left(\frac{{\partial Yield}/{\partial S}}{{Yield}/{Yield_{threshold}}}\right) \qquad (2)$$

where ${\partial Yield}/{\partial S}$ is the estimated response of yields to stressor S, $Yield$ is the observed yield in a given system (county) and $Yield_{threshold}$ represents the point of reference for a given system below which the agricultural sector becomes "damaged".

The marginal effects of stressors across yields are obtained from an econometric model widely used in the literature. The specification relies on historical data on yields, temperature and precipitation to estimate the effects of climate change on agricultural output (Deschenes and Greenstone, 2007; Kaylen, Wade and Frank, 1992; Schlenker and Roberts, 2006; Schlenker and Roberts, 2009, among others).

$$Y_{ijt} = \sum_{\mathrm{g}=1}^{4}\left[\alpha_{1\mathrm{g}}\mathrm{Prec}_{\mathrm{ijtg}} + \alpha_{2\mathrm{g}}\mathrm{Temp}_{\mathrm{ijtg}}\right] + \gamma'\mathrm{F}_{\mathrm{j}} + \mathrm{n}'\mathrm{F}_{\mathrm{i}} + \mathrm{t} + \mathrm{trend} + \varepsilon_{\mathrm{ijt}} \qquad (3)$$

Where $\mathrm{Y}_{\mathrm{ijt}}$ is the yield of crop j in municipality i at year t, $\mathrm{Prec}_{\mathrm{ijtg}}$ is cumulative precipitation in stage g of the growing season. $\mathrm{Temp}_{\mathrm{ijtg}}$ is the average temperature in stage g of the growing season. The set of variables F_{i} and F_{j} denote time invariant characteristics at the county and crop levels respectively. To control for state and nationwide changes over time, such as technological progress (i.e. introduction of new seed varieties), we include a trend and year fixed effects (t). Also, we specified fixed effects by crops in order to estimate a sensitivity indicator per crop.

The third component, the local vulnerability indicator, is defined as the expected value of the sensibility indicators for the different stressors. The expected value is calculated over the domain of the climate empirical probability distribution obtained from random realizations of the accumulated precipitation and average temperature given by the historical records at the municipality level. System vulnerability depends on the exposure levels to a given stressor, which is given by the probability distribution of the stressor in a given system. Thus, a vulnerability indicator can be defined as the expected value of the ratio of the system's sensitivity to a given threshold:

$$V = \ Expected\, Value[SS] = \int \left(\frac{{\partial Yield}/{\partial S}}{{Yield}/{Yield_{threshold}}} \right) Pr_S dS \qquad (4)$$

where Pr_S refers to the density function of stressor S.

In practice, the metric of this indicator allows ranking systems with different yield performance, exposure to climate risk and different levels of sensibility. Thus, even when two systems show the same level of exposure, their vulnerability indicators could differ depending on yield performance and sensitivity. For example, with two stressors (precipitation and temperature) equation (4) is calculated as:

$$V = \int \int \left(\frac{{\partial Yield}/{\partial Prec} + {\partial Yield}/{\partial Temp}}{{Yield}/{Yield_{threshold}}} \right) Q(Prec, Temp) dPr_{Prec} dPr_{Temp} \qquad (5)$$

where the term $Q(Prec, Temp)$ corresponds to the joint probability distribution function of the two stressors; dPr_{Prec} and dPr_{Temp}refers to the marginal distributions of precipitation and temperature respectively. By the Radon-Nikodym theorem,[3] we can treat every component of the vulnerability indicator as independent and re-express equation (5) as:

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[3] The Radon-Nikodym theorem allows expressing probability masses and probability densities over real numbers from probability measures defined over arbitrary sets. It tells if and how it is possible to change from one probability measure to another.

$$V = \int \left(\frac{{\partial Yield}/{\partial Prec}}{{\widehat{Yield}}/{Yield_{threshold}}} \right) dPr_{Prec} + \int \left(\frac{+\,{\partial Yield}/{\partial Temp}}{{\widehat{Yield}}/{Yield_{threshold}}} \right) dPr_{Temp} \quad (6)$$

The expectation is calculated using Monte Carlo simulation that samples from observe data distribution 10,000 times, so the local vulnerability indicator is obtained by averaging the means of the function evaluated at the particular values obtained in every sample for precipitation and temperature.

The evaluation of systems' adaptive capacity (AC) reflects the magnitude to which a system can be modified to become less vulnerable. Thus, an AC valuation can be defined as the difference in terms of vulnerability from the existing conditions (ec) with respect to modified conditions (mc):

$$AC = V(mc) - V(ec) \qquad (7)$$

Because we are focusing on the agricultural sector, the stressors are functions of precipitation and temperature, whereas exposure is given by the probability density distribution function of the stressors under different climate change scenarios, including a baseline scenario without climate change. For each system (county), we will calculate equations (6) and (7) using georeferenced projected climate change scenarios from several Global Climate Models (GCMs). Once equations (6) and (7) are estimated, we can rank municipalities according to their vulnerability to climate change, assess their adaptive capacity and identify their main drivers. These drivers can inform policy to reduce vulnerability, increase system resiliency and to direct investments to successful adaptation strategies.

The proposed local vulnerability evaluation methods are robust according to the Adger's criteria (Adgers, 2006). These evaluations are tractable because they can be compared across time and location; they also capture how the dynamics and the spatial interaction of the biophysical and social processes shape local conditions and the ability of systems to adapt. In addition, our evaluation of local vulnerability to climate change in the agricultural sector is able to capture two important types of changes that describe system dynamics: 1) changes in the severity of climate change within systems and distribution of risks across systems; 2) changes in the risk distribution.

3. *Agriculture and the "Development Program for the Southwest Region of the State of Tocantins (PRODOESTE) in Tocantins, Brazil*

In the last decades Brazil has become one of the most important soybeans producer in the world. An important soybeans development area is located in low latitude lands in Central and North Brazil, the Cerrado region, where the State of Tocantins is located. Dry winters and rainy summers characterize the Cerrado climate, where the growing season is largely determined by the occurrence of seasonal rain.

The development of irrigation systems in the Cerrado facilitates the production of grains and seeds, especially soy, rice, corn, beans, watermelon and other crops, in dry autumn and winter months. Topographical relief and a broad latitude distribution result in wide variations of temperature, although average temperature during the coldest months rarely falls below 18°C. Despite 95 percent of Cerrado's soils are poor in nutrients and acids, the Cerrado land is adequate for soy cultivation. Average annual precipitation varies between 750mm to 1,500mm, with maximums of 2,000mm. The dry season occurs between May and September and any agricultural activity during this time requires irrigation. Rainfall occurs mainly between October and March (Figure 1). Drought is usually the main factor responsible for crop losses. The two most critical periods for drought stress in soybeans production are from seed emergence to seedling establishment and the grain filling period (Silva et al., 2013).

The agricultural sector is important for Tocantins' economy since it represents 17.8% of the state GDP. Agriculture in Tocantins is sensitive to climate conditions since it is mainly conducted in rain-fed areas. During the dry season, rivers in the basins of Pium and Riozinho poorly distribute the seasonal rain, causing water shortages in irrigation systems across Tocantins. For this reason the development of irrigation systems in the region has been an important strategy to improve its agricultural potential.

Thus, the Development Program in the Southwest Region of the State of Tocantins (PRODOESTE) focuses on improving water supply and providing with technical support to farmers located in Southwest Tocantins, in order to increase the number of harvests per year from

1 to 2.5 and incentivize the cultivation of crops with more commercial value. PRODOESTE covers 14 municipalities of the 139 municipalities of the State of Tocantins (Figure 2). In its first stage, PRODOESTE will provide irrigation for 7,100 hectares located in the Pium and Riozinho river basins (IADB, 2013a). Program beneficiaries are rice, soybeans, watermelon, beans, sunflower and corn farmers that with land plots between 160 ha and 19,700 ha.

The project intends to achieve the following yields: Rice 6 ton/ha; Soybeans 3 ton/ha; Corn 6 ton/ha; Beans 2.2 ton/ha and Watermelon 25 ton/ha. Other expected results of the project are to increase: 1) farmer's profits from R$103 to R$1970 and 2) the number of direct and indirect jobs from 0 to 34,540 (IADB project number BR-L1152).

Main crops planting dates are from October to May. Soybeans main cycle is from November to March with the main requirements of precipitation during December, while corn's main cycle is from December to March. Rice´s main cycle is from January to May and it is mainly grown in irrigated land. Watermelon is also grown in irrigated areas (Table 1). In general, rotation is a usual practice to break disease and insect cycles and also for decreasing erosion: rice grows in rotation with beans and watermelon rotates with rice in low land areas under sub-irrigation; soybeans grow in rotation with corn.

In most of Tocantins areas, climate risk is high from May to July. In particular, drought risks and increases in temperature can have a significant negative effect on water balance, via an increase in potential evapotranspiration (Silva et al., 2010). In addition, water stress results in slow growth by reducing plant cell reproduction. Potential harm from drought depends on its duration and the type of species and genotypes/cultivar affected.

4. *Data sources and management*

We assess local vulnerability to climate change in agriculture for those municipalities where PRODOESTE operates; we mainly evaluate the potential impact of climate change on the agricultural systems' crop yields and relate it to Tocantins farmer's profits. We focus on yields rather than land values or directly on profits because yields are measurable on a more continuous basis by the Brazilian statistical agency (IBGE). Although, we do not directly assess vulnerability as a monetary function, we will convert our vulnerability indicator to monetary values as it is showed in the monetary valuation section.

4.1. Crop yields data

Since Brazil has data on crop yields at the local level (county-level), we evaluate the effects of climate change on crop yields using historical data and regression techniques. Table 2 shows the agricultural profile of PRODOESTE's municipalities for the period 2001-2012. Rice, corn and soybeans are the most cultivated crops in those municipalities. Some other municipalities also cultivate watermelon and beans.

Since 2008, soybeans and beans cultivated area has been increasing in PRODOESTE's municipalities whereas corn cultivated area has decreased (Figure 3).

Although yields of cultivated grains in PRODOESTE's municipalities are relatively low, they have increased over time. Yields of rice, corn and soybeans are almost 3 tons/ha and of beans are around 1.2 tons/ha (Figure 4).

4.2. Historical climate data

Unfortunately public daily data available on climate for Brazil has lots of missing information,[4] hence we were not able to construct more accurate measures of temperature such as growing degree days, heating degree days or, even more detailed variables such as Chebyshev polynomials of temperature of the number of hours during the growing season a crop is exposed to a given temperature range as in Roberts and Schlenker (2006, 2009). We therefore use the average monthly temperature and precipitation from 2001 to 2012 reported by the HadCM3 model from the Climate Research Unit of the University of East Anglia (http://www.cru.uea.ac.uk/~timm/grid/TYN_SC_2_0.html).

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[4] Initially, we focused on two sources of weather station data for Brazil, National Oceanic and Atmospheric Administration (NOAA) and INPE (http://sinda.crn2.inpe.br/PCD/historico/consulta_pcdm.jsp). NOAA's site has data from 1992 to 2002 and we tried to interpolate the data to generate a geographic continuum of temperature and precipitation; however, the resulting database had many missing values. On the other hand, INPE's data is relatively better for the later period 2002-2013, but it also has lots of missing information for some weather stations.

Tocantins' agricultural production occurs during eight months of the year, from October to May. Hence we divided Tocantins growing season in four sets of two-month periods each to better reflect water and temperature crop needs by phenological stage. Table 3 shows descriptive statistics of average temperature and cumulative precipitation for each growing season stage. Precipitation is notably concentrated in the months of December to March, which coincides with the flowering and grain filling periods of soybeans and corn. Figure 5 shows average accumulated precipitation and average temperature during each stage of the growing season from 2001 to 2012. In Panel a) we can notice a downward trend in terms of accumulated precipitation during the first and last stages of the growing season, whereas no clear trend can be appreciated for stages 2 and 3. From Panel b) we observe that October and November are the warmest months, whereas December and January are the coldest. More importantly, most of the average temperatures by growing stage show increasing trends since 2006.

4.3. Climate change data

Climate scenarios for Brazil from different models predict a decrease in precipitation and an increase in average temperature for both long-term (2070-2099) and medium-term (2020-2049) horizons. Table 4 shows the precipitation percentage changes scenarios for PRODOESTE's municipalities with respect to historical means (2001-2012) during the growing season, as projected by the HadCM3 model under IPCC scenarios of "rapid economic growth dependent on fossil fuels" (A1F1), "heterogeneous world with an emphasis on family values and local traditions" (A2), "introduction and prevalence of clean technologies" (B1) and "emphasis on local solutions to economic and environmental sustainability" (B2). According to Table 4 there is a high degree of heterogeneous impacts across municipalities and horizons. While in the medium-term Lagoa da Confusão will experience the largest reductions in precipitation for the A1F1 scenario (-7.37%), in the long-term it will be Talismã (-55.54%).

Projected temperature changes will also be large. Table 5 shows temperature percentage change scenarios for PRODOESTE's municipalities from historical means (2001-2012) during the growing season. All of the scenarios and the horizons predict increases in average temperature, however the impacts, compared to precipitation projections, seem to be more homogeneous across municipalities, ranging from 4.89% to 5.67% under the business as usual scenario (A1F1).

5. *Exposure*

As mentioned before, the analysis of every component of local vulnerability was carried out considering the five main crops for the municipalities where PRODOESTE is operating: soybeans, corn, rice, watermelon and beans.

The local exposure indicator (equation 1) reflects at the system-level the varying magnitudes and frequencies of stressors' realizations and for every growing season stage, it is defined an exposure indicator based on the number of times historical temperature and precipitation during each stage of the growing season felt outside a given range, appropriate for crop development.

Every crop has a particular range of maximum temperature, minimum temperature and precipitation within which growth is suitable (Table 6). A range of temperatures and accumulated precipitation for all crops was determined to obtain the exposure indicator as a frequency indicator that accounts for historical climate realizations outside this range. Hence, in practical terms the exposure indicator measures the probability that in a given municipality the climate variable (precipitation or temperature) exceeds a threshold that will be detrimental for crop growth.

From the distribution of the exposure indicator in Tocantins we defined the following categories for temperature: highly exposed agricultural systems show indicators higher than 0.23; medium exposed agricultural systems exhibit indicators from 0.021 to 0.23; whereas low exposed agriculture systems show indicators lower than 0.021. In terms of precipitation, highly exposed systems exhibit indicators higher than 0.396, medium exposed are between 0.312 and 0.396, and low exposure systems present values lower than 0.312 (Table 7).

For the baseline assessment, exposure indicators are wide-ranging by municipality and stressor. PRODOESTE's municipalities mostly show high to medium temperature and precipitation exposure, relative to the rest of Tocantins. Temperature exposure in PRODOESTE's municipalities is higher than average exposure in Tocantins municipalities. In terms of the precipitation stressor, six of the fourteen municipalities show exposure rates above Tocantins' average (Table 7).

6. Sensitivity

The fixed effects model in equation (3) was used to estimate crop yields as a function of temperature and precipitation variables considering the 139 municipalities of Tocantins and the five main crops, soybeans, rice, corn, watermelon and beans, from 2001 to 2012.

We also experimented with estimating equation (3) for each crop removing the crop fixed effects, however, since not all municipalities cultivate all crops, the number of observations were highly reduced for some crops (i.e. watermelon), yielding non-statistically significant coefficients. Additionally, non-linear terms on the temperature and precipitation variables were also included, but proved to be highly unstable in our specification, hence we opted for removing those terms and having a more consistent and parsimonious model. In general, the model captures the introduction of genetical modified varieties of soybeans, but this effect could appear weak because of the mixed effect in data from input-intensive commercial growers who more frequently change their seed stock in comparison to subsistence or less input-intensive producers that have being grown traditional varieties for decades in some locations (Pardey et al., 2004).

Table 8 shows the estimates of equation (3). An increment of 1% in accumulated precipitation during the second and third stages of the growing season increase yields by 0.09% and 0.1%, respectively. In contrast, the temperature effect is stronger: the highest effect is during the first stage of the growing season, which is during the vegetative period of soybeans that require an average temperature of 30°C. A 1% increase of average temperature in the second stage of the growing season increases yields by 2.2% and decreases yields by 0.4% if registered during the third stage. For a detailed report on the econometric estimation, see Table 15 in Annex A.

Given the marginal effects of stressors on yields, the yield threshold for every crop and the elasticity of profits with respect to income, the sensitivity indicator is calculated as in equation (1). As a consequence of the higher estimators of marginal effects of temperature on yields, temperature sensitivity indicators are higher than precipitation sensitivity indicators.

6.1. Monetary valuation

In order to convert our sensitivity and vulnerability indicators into monetary values, first we estimate an econometric model to explain farmers' profits as function of yields, via the following equation.

$$\pi_{it} = \rho' Y_{it} + St + t + \varepsilon_{it} \qquad (8)$$

Where π_{it} represent average profits reported by farmers in municipality i in census year t, St represent state by time fixed effects, t represents time dummies and Y_{it} are average crop yields. Hence, to translate our parameters of interest (α in equation 3) into monetary values we weight them by the parameters ρ estimated in equation (8). Hence, the term $\alpha'\rho$ represents climate-profits elasticities for each crop.

Since profits are only measured every ten years (with the agricultural census), we estimate a two period (1995 and 2006) equation at the municipality level for all Brazil, one for each crop. Table 9 shows estimates for equation (8). Profits seem to respond heterogeneously to crops. Beans yields have the strongest correlation with profits, whereas watermelon the lowest.

The monetary conversion of the sensitivity indicator modifies the interpretation of the indicators. For the temperature indicator it can be interpreted as the percentage change in profits due to a one percentage increase in temperature. In order to obtain an aggregated sensitivity indicator (not by crop), we compute the weighted sum of crop sensitivity indicators by municipality, where weights are given by the share of the total value of production of soybeans, corn, watermelon, beans and rice production in the municipality during the period 2001-2012.

Almost all municipalities where PRODOESTE operates show high sensibility of profits as a response of the effect of temperature on beans yields. The lowest temperature sensitivities were found for rice and watermelon (Table 10). In terms of sensitivity by crop, the municipality of Formoso do Araguaia shows the highest indicator of sensitivity to precipitation (0.081) in the production of soybeans and Talismã an indicator of 0.065 for the production of beans. In the aggregate, municipalities of Formoso do Araguaia, Pium and Sandolândia show the highest levels of precipitation sensitivity.

In terms of sensitivity to temperature, the production of soybeans shows higher levels of sensitivity to temperature for PRODOESTE than for all Tocantins, being the municipalities of Aliança do Tocantins, Sandolândia and Santa Rita do Tocantins the ones with the highest sensitivity (around 2.6, 2.1 and 2.1 respectively). Regarding aggregate sensitivity, PRODOESTE's municipalities show higher values than Tocantins average. Formoso do Arrigunaia presents the highest sensitivity indicator (2.33).

7.1 Vulnerability

Based on equation 6, Table 11 shows the vulnerability assessment by municipality where PRODOESTE operates, which is notably higher for soybeans production for both stressors, while for the production of watermelon is the lowest. Santa Rita do Tocantins and Aliança do Tocantins show the highest temperature vulnerability.

Figure 6 shows the precipitation vulnerability map at the municipality level. There is a lot of heterogeneity in terms of vulnerabilities across PRODOESTE's municipalities although most of the municipalities present medium to high levels of precipitation vulnerability. Highly vulnerable PRODOESTE's municipalities are located in the South side of PRODOESTE, whereas low precipitation vulnerable municipalities locate on the West side.

Figure 7 depicts the temperature vulnerability map for Tocantins. Also, most of PRODOESTE's municipalities show medium to high temperature vulnerability levels. In contrast with precipitation vulnerability, medium temperature vulnerable municipalities locate to the West side of Tocantins, whereas low temperature vulnerable municipalities are located in the Southwest side.

7.1.Climate change assessment

For the construction of the components of the vulnerability indicators under climate change scenarios, we replaced historical data with climate change scenarios data. In particular, the econometric model of equation (3) was re-estimated for four scenarios (A1F1, A2, B1, B2) and two horizons (medium-term and long-term).

7.1.1. Sensitivity

For the construction of the sensitivity indicators, equation (2), we kept fixed the estimated coefficients of the marginal effect of stressors on yields from historical data (Table 8) as well as the threshold. We re-estimated the projected yield (denominator in equation 6) for every scenario. Table 12 shows the aggregate indicators for sensitivity. Climate change will likely increase the sensitivity of agricultural local systems.

As expected, the sensitivity indicator increases with more extreme scenarios (A1F1) and in the long-term. Long-term A1F1 scenarios are two-fold higher than A1F1 medium-term scenarios. In general terms, Alvorada, Cariri do Tocantins and Talismã show the highest levels of sensitivity as a result of climate change.

7.1.2. Vulnerability

We calculated the vulnerability indicators keeping the estimated coefficients of the marginal effect of stressor on yields and the thresholds fixed and just changed the projected yield. Hence, the estimated yield (denominator in equation 4) changes for every scenario.

Table 13 shows the local vulnerability indicators for different climate change scenarios. In general, vulnerability increases with more extreme scenarios such as A1F1 and in the longer term. The most conservative greenhouse gas (GHG) emissions scenario, B1, presents the lowest vulnerability.

Long-term scenarios seem particularly alarming in terms of temperature vulnerability. Municipalities such as Araguacú and Dueré show low vulnerability levels across all scenarios. In contrast, municipalities such as Alianza do Tocantins, Formoso do Araguaia and Pium remain as the most vulnerable across climate change scenarios.

Figures 8 and 9 show medium-term A1F1 scenario differences between climate change and baseline vulnerability levels for precipitation and temperature, respectively. In the medium-term, PRODOESTE’s municipalities predominately will show medium increases in terms of precipitation vulnerability. In the case of temperature vulnerability, two municipalities will experience high increases in their vulnerabilities and most of the rest will experience medium increases. Additional vulnerability maps for climate change scenarios B1, A2 and B2 in the long-term are in Appendix B, Figures B.1 – B.8.

7.1.3. Adaptive capacity

We focus on the irrigation as a potential strategy to cope with climate change in Tocantins municipalities. Our assessment is done by conducting separate estimates of the effects of climate stressors on yields for municipalities with a share of irrigated land higher than the average (High Irrigation) of all municipalities in Tocantins and municipalities with a share of irrigated land lower than the average (Low Irrigation), see Table A.3. in Appendix A. To assess how irrigation can potentially change vulnerability in Low Irrigation municipalities we impute their marginal effects by those of High Irrigation municipalities.

To assess how vulnerability can improve due to adaptation via irrigation we first calculate vulnerability indicators for each Low Irrigation municipality using their baseline estimates and using the High Irrigation estimates. Then we calculate the differences of those indicators under climate change scenarios. Table 14 displays aggregate adaptive capacity indicators for Tocantins which capture how on average vulnerability indicators change in percentage points as a result of adaptation. Results are consistent within scenarios; adaptive capacity (vulnerability reduction) is stronger for more extreme scenarios (A1F1). Medium-term horizon results show temperature vulnerability reductions although they are not conclusive regarding precipitation vulnerability. In the long-term, vulnerability decreases for both precipitation and temperature stressors, and the effect is stronger for the later. In general terms, our model predicts that adaptive capacity will be higher for more extreme scenarios of climate change.

8. Conclusions

This paper develops and applies a methodology for estimating local agriculture vulnerability indicators for Brazil. The methodology heavily relies on public available weather and crop yields data at the municipality-level. We apply our methodology to the state of Tocantins in Brazil, where the Development Program for the Southwest region of the state of Tocantins (PRODOESTE) is being implemented, and focus our analysis on the main cultivated crops targeted by PRODOESTE: rice, corn, soybeans, beans and watermelon. The main advantage of our indicators is that they can be applied to cases where there is publicly available data on crop yields, farmers' profits and weather data.

The proposed indicator of local vulnerability includes the assessment of all its elements: exposure, sensitivity, vulnerability and adaptation (the capacity to build resilience), capturing systems' dynamics on intensity and how climate events modify adaptive capacity. Also the flexibility of the indicator allows ranking systems with different yield performance, different exposure to climate risk and different levels of sensibility. Thus, even when two systems show the same level of exposure, their vulnerability indicators can differ depending on yield performance and sensitivity.

The vulnerability indicator is composed of two parts, exposure and sensitivity, and it is measured at the system-level, in this case the municipality-level. System exposure is measured as the probability that temperature and precipitation (the stressors) fall outside a given range that is appropriate for crop development. Thus, exposure measures the propensity of the system to be damaged. Sensitivity is computed as the marginal effect of the stressor on crop yields, weighted by the inverse ratio of the yield to a threshold yield which represents the yield level below which the system is damaged or, in economic terms, the crop investment is lost. Hence, sensitivity will be higher if the marginal effect of the stressor on the crop yield is high and the closest the average crop yield is to the threshold. Vulnerability is then calculated for each stressor, temperature and precipitation, as the expected value of the sensitivity measure, where the expectation is taken over the exposure domain. In general terms, it measures the expectation that the system can be damaged as a response of changes in the stressors (temperature and precipitation).

In order to convert our measures to monetary values, we estimate the profits-yield elasticities for each of the crops evaluated and weight our vulnerability measures by the profits-yield elasticities. Our baseline results indicate that PRODOESTE's municipalities present medium to high levels of precipitation and temperature vulnerability. In general terms, the South side of PRODOESTE shows the largest vulnerabilities to precipitation and the east side presents the highest temperature vulnerabilities.

In a further step, we estimate the possible effects that climate change may have on temperature and precipitation vulnerability and we find that more extreme scenarios of GHG emissions combined with longer horizons will highly increase vulnerability. Finally, we perform an adaptation exercise where we divide our sample in two: municipalities that have a percentage of farms with irrigation higher than the average in Tocantins (High Irrigation) and municipalities that have a percentage of farms with irrigation lower than the average in Tocantins (High Irrigation). We then re-estimate our vulnerability measures for Low Irrigation areas and impute the sensitivity values of the High Irrigation areas into the Low Irrigation areas. We therefore, obtain a vulnerability measure accounting for adaptation. In general, accounting for adaptation, we obtain that vulnerability will be reduced, especially in the long-term.

9. References

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10. Table Annex

Table 1. Climate vs. Main crops and agronomical relevant dates

Month	Precipitation Mm/day	Precipitation	Minimum Temp. °C	Maximum Temp. °C	Temperature	Soybeans	Corn	Rice	Watermelon
September	4.3	Rain season starts.	20.1	33.9	High temperatures	Soil preparation			Harvest time under irrigation.
October	8.5	Rains show their pick, it rains daily 2 - 3 times per day.	21.0	34.3	Temperatures increasing and reaching its maximum	Planting of early season in late September	Planting of early season in late September		
November	9.3	Rains decrease, it rains 3-4 time per week.	21.0	32.8	Temperatures remain high and decreasing	Early November is the main soybean planting period, planting in full swing	Planting in full swing, first early season		
December	10.3	Rainfall frequency picks up in Brazil, rains 1-2 times a week, distribution may be uneven	20.6	31.4	Cloud cover and rain holds temperatures in the 90's.	Harvesting time for soybeans under irrigation. Finish soybean planting and earliest planted soybeans may start flowering by end of the month.	Early planted corn begins pollination.		
January	10.0	Soybeans flowering and setting pods.	20.7	30.4	Cloud cover and rain holds temperatures in 25°c's.	Begin spraying to control soybean rust	Corn crop completes pollination and begins grain filling	Planting time under irrigation.	
February	9.6		20.9	30.4		Main pod filling month for soybeans. Soybean rust control now focused on later maturing soybeans.	Safrinha (second corn crop) planted after early soybeans are harvested.		
March	8.9	Rains become more scattered.	21.2	30.7	Weather becomes dryer by the end of the month, Temperatures become more moderate	Main soybean harvesting month. Soybean exports in full swing.	Full-season corn harvest wraps up. Safrinha corn crop in vegetative phase.		Planting time under irrigation.
April	6.9	starting to dry out	20.8	30.8	Temperatures ease to more moderate levels	Soybeans for exportation.	Safrinha corn crop in late vegetative stage or early reproductive		
May	3.8	Scattered rains continue	19.8	31.3	Temperatures are warm in central Brazil		Safrinha corn filling grain, early-planted safrinha corn harvest begins	Harvesting time under irrigation	
June	2.1	Dry season, sparse rain	18.1	31.9	Cool temperatures		Remainder of safrinha corn is harvested during this period		
July	1.2	Dry season, sparse rain	17.4	32.2	Cool temperatures with occassional light frost				
August	1.8	Dry season, sparse rain	18.1	32.7	Cool temperatures	Planting time for soybeans irrigated.			

Source: www.primaveracrops.com and Silva et al. (2013).

Table 2. Average annual crop yields (ton/ha) and cultivated area (ha) for PRODOESTE's municipalities (2001-2012)

	Rice		Beans		Watermelon		Corn		Soybeans	
Municipalities	Yields	Cultivated Area	Yields	Cultivated Area	Yields	Cultivated Area	Yields	Cultivated Area	Yields	Cultivated Area
ALIANÇA DO TOCANTINS	2.57	612.50	-	-	-	-	2.05	345.00	2.42	827.50
ALVORADA	1.90	303.33	0.60	5.00	32.67	20.00	3.24	573.92	2.77	4687.50
ARAGUAÇU	1.70	889.17	-	-	25.50	23.00	2.64	1258.33	2.55	861.00
CARIRI DO TOCANTINS	1.73	657.50	1.43	316.67	23.78	13.75	2.20	545.00	2.53	1781.82
CRISTALÂNDIA	2.95	1601.25	1.59	600.00	23.33	112.83	2.32	590.83	2.40	250.00
DARCINÓPOLIS	2.08	1866.67	0.49	111.67	-	-	2.14	1184.17	2.40	3670.45
DUERÉ	4.18	5128.33	1.61	1986.00	31.88	25.00	2.22	372.92	2.46	1861.29
FIGUEIRÓPOLIS	1.80	995.83	1.93	101.67	30.85	23.75	3.11	802.08	2.87	4301.42
FORMOSO DO ARAGUAIA	4.54	18671.58	1.42	190.00	34.10	1715.25	2.38	1052.08	2.72	14189.00
LAGOA DA CONFUSÃO	4.23	25991.67	1.77	4359.17	24.58	1684.17	3.89	716.25	2.58	10823.25
PIUM	3.34	4407.50	1.59	660.00	10.00	30.00	2.19	1133.33	2.57	1694.60
SANDOLÂNDIA	1.67	468.33	-	-	-	-	1.86	675.50	2.50	90.00
SANTA RITA DO TOCANTINS	1.98	2285.00	-	-	-	-	1.64	405.00	2.46	805.00
TALISMÃ	1.72	164.17	0.60	10.00	-	-	3.41	1037.50	2.77	1837.50

Source: IBGE.

Table 3. Summary statistics of climate variables for Tocantins

Variable	Mean	Std. Dev.	Min	Max
	Accumulated Precipitation (mm)			
Growth Stage 1 (Oct-Nov)	261.19	87.39	85.93	526.28
Growth Stage 2 (Dec-Jan)	480.69	118.48	152.25	793.10
Growth Stage 3 (Feb-Mar)	481.38	107.54	254.59	727.74
Growth Stage 4 (Apr-May)	200.40	94.95	12.48	527.56
Complete Season (Oct-May)	**1,423.66**	**206.17**	**882.18**	**1,929.89**
	Average Temperature (°C)			
Growth Stage 1 (Oct-Nov)	27.65	0.58	25.40	29.26
Growth Stage 2 (Dec-Jan)	26.42	0.62	23.98	28.28
Growth Stage 3 (Feb-Mar)	26.74	0.73	23.96	28.61
Growth Stage 4 (Apr-May)	27.14	0.88	23.61	28.90
Complete Season (Oct-May)	**26.99**	**0.63**	**24.53**	**28.39**

Source: Own estimations.

Table 4. HadCM3 model precipitation change from historical means during growing season (%)

	Medium-Term (2020-2049)				Long-Term (2070-2099)			
Municipalities	A1F1	A2	B1	B2	A1F1	A2	B1	B2
ALIANÇA DO TOCANTINS	-4.60	-1.53	-1.38	-1.97	-50.33	-27.56	-11.92	-14.41
ALVORADA	-4.28	-0.20	-0.21	-0.25	-54.55	-23.30	-10.03	-10.57
ARAGUAÇU	-4.16	-0.13	-0.12	-0.08	-50.52	-20.70	-8.90	-9.12
CARIRI DO TOCANTINS	-4.83	-1.28	-1.17	-1.47	-51.96	-25.37	-11.10	-12.53
CRISTALÂNDIA	-5.41	-3.14	-3.47	-4.08	-46.94	-30.89	-15.76	-18.46
DARCINÓPOLIS	-1.46	0.43	1.28	-0.01	-44.18	-30.62	-9.50	-14.46
DUERÉ	-5.19	-2.16	-1.96	-2.54	-49.95	-27.65	-12.22	-14.64
FIGUEIRÓPOLIS	-4.28	-0.20	-0.21	-0.25	-54.55	-23.30	-10.03	-10.57
FORMOSO DO ARAGUAIA	-6.14	-2.91	-2.88	-3.11	-50.28	-26.81	-12.93	-14.15
LAGOA DA CONFUSÃO	-7.37	-4.59	-4.78	-5.43	-50.38	-30.42	-16.06	-18.81
PIUM	-6.75	-4.58	-4.94	-5.63	-46.66	-31.66	-17.07	-20.05
SANDOLÂNDIA	-5.51	-1.95	-1.89	-1.88	-50.91	-24.81	-11.45	-11.84
SANTA RITA DO TOCANTINS	-5.34	-2.83	-2.93	-3.58	-48.03	-29.92	-14.46	-17.25
TALISMÃ	-3.81	0.41	0.39	0.41	-55.54	-22.73	-9.45	-9.78

Source: Own estimations with data from the Climate Research Unit of the University of East Anglia.

Table 5. HadCM3 model temperature change from historical means during growing season (%)

	Medium-Term (2020-2049)				Long-Term (2070-2099)			
Municipalities	A1F1	A2	B1	B2	A1F1	A2	B1	B2
ALIANÇA DO TOCANTINS	5.37	4.25	4.13	4.52	18.15	14.67	9.20	10.37
ALVORADA	5.56	4.45	4.32	4.70	18.18	14.70	9.30	10.41
ARAGUAÇU	5.56	4.45	4.32	4.70	18.26	14.80	9.32	10.46
CARIRI DO TOCANTINS	5.38	4.26	4.14	4.51	18.10	14.60	9.18	10.29
CRISTALÂNDIA	5.17	4.05	3.91	4.38	18.43	14.97	9.23	10.59
DARCINÓPOLIS	5.07	3.95	3.64	4.33	18.94	15.48	9.06	10.95
DUERÉ	5.23	4.11	4.00	4.39	18.03	14.55	9.09	10.26
FIGUEIRÓPOLIS	5.56	4.45	4.32	4.70	18.18	14.70	9.30	10.41
FORMOSO DO ARAGUAIA	5.00	3.93	3.78	4.18	17.60	14.23	8.74	9.93
LAGOA DA CONFUSÃO	4.89	3.80	3.64	4.10	17.92	14.52	8.80	10.15
PIUM	5.03	3.91	3.75	4.26	18.42	14.96	9.11	10.55
SANDOLÂNDIA	5.15	4.07	3.93	4.31	17.71	14.30	8.86	10.00
SANTA RITA DO TOCANTINS	5.17	4.05	3.93	4.37	18.26	14.79	9.16	10.44
TALISMÃ	5.67	4.56	4.44	4.82	18.27	14.81	9.41	10.52

Source: Own estimations with data from the Climate Research Unit of the University of East Anglia.

Table 6. Agronomical criteria for stressors by crop

Crop	Duration in days of growth cycle*	Prcipitation Mm per day	Optimal Temperature for Reproduction oC	Optimal Temperature Range for Yield oC	Failure Temperature Reproductive yield oC
Soybeans	90-130	7-8 mm	34	25-37	39
Corn	110-120	8 mm	26	18-25	35
Rice	120-140	7-8 mm	33	23-27	35-36
Watermelon	120-130	5 mm	35	22-30	37
Beans	140-150	6 mm	--	23-24	32

* Depends on variety.

Source: Hatfield et al., 2011; Silva et al., 20013.

Table 7. Exposure Indicators. Baseline assessment

	Exposure index*			
Municipalities	**Temperature**		**Precipitation**	
1. Aliança do Tocantins	0.167	M	0.396	H
2. Alvorada	0.021	L	0.479	H
3. Araguaçú	0.021	L	0.479	H
4. Cariri do Tocantins	0.021	L	0.438	H
5. Cristalândia	0.229	H	0.375	M
6. Crixás do Tocantins	0.187	M	0.375	M
7. Dueré	0.187	M	0.417	H
8. Figueirópolis	0.021	L	0.479	H
9. Formoso do Araguaia	0.229	H	0.458	H
10. Lagoa da Confusão	0.250	H	0.438	H
11. Pium	0.271	H	0.375	M
12. Sandolândia	0.083	M	0.458	H
13. Santa Rita do Tocantins	0.229	H	0.396	H
14. Talismã	0.021	L	0.375	M
PRODOESTE Average	**0.138**	M	**0.424**	H
Tocantins Average	**0.128**	M	**0.348**	M

*Frequency indicator.

Source: Own estimations.

Table 8. Marginal effects estimates of stressors on yields

Variable	Estimator	Std. Err.
All Crops		
Ac. Precipitation, Stage 1 (Oct-Nov)	0.007	0.015
Ac. Precipitation, Stage 2 (Dec-Jan)	0.091 ***	0.018
Ac. Precipitation, Stage 3 (Feb-Mar)	0.099 ***	0.022
Ac. Precipitation, Stage 4 (Apr-May)	-0.016	0.011
Av. Temperature, Stage 1 (Oct-Nov)	3.380	0.577
Av. Temperature, Stage 2 (Dec-Jan)	2.212 ***	0.785
Av. Temperature, Stage 3 (Feb-Mar)	-0.443 ***	0.805
Av. Temperature, Stage 4 (Apr-May)	0.573	0.644

Source: Own estimations.

Note: *, **, and ***, significance level of estimates at 10%, 5% and 1%, respectively.

Table 9. Ordinary Least Squares (OLS) Regression of Profits as a Function of Yields

	Beans	Corn	Rice	Soybeans	Watermelon
Yield	0.415***	0.338***	0.198***	0.347***	0.135***
	(0.031)	(0.031)	(0.037)	(0.100)	(0.03)
State by year FE	Y	Y	Y	Y	Y
Observations	7897	8446	6370	2710	2829
R-squared	0.292	0.2897	0.301	0.186	0.317

Note: Each column represents a different regression according to the crop. Both dependent and independent variables are in logs. State level clustered standard errors in parenthesis, *, **, ***, significant at 10%, 5% and 1%, respectively.

Source: Own estimations.

Table 10. Sensitivity indicators by crop and aggregate.

Baseline assessment

Municipalities	Soybeans	Rice	Corn	Watermelon	Beans	Aggregate
	Sensitivity to Precipitation					
1. Aliança do Tocantins	0.0679	0.0333	0.0505	0.0230	0.0621	**0.0522**
2. Alvorada	0.0546	0.0262	0.0397	0.0199	0.0458	**0.0452**
3. Araguaçú	0.0458	0.0217	0.0328		0.0350	**0.0425**
4. Cariri do Tocantins		0.0322	0.0488	0.0269	0.0600	**0.0480**
5. Cristalândia (1ª Etapa)	0.0427	0.0204	0.0309	0.0158	0.0374	**0.0395**
6. Crixás do Tocantins	0.0505	0.0217	0.0329			**0.0345**
7. Dueré	0.0000	0.0301	0.0457			**0.0400**
8. Figueirópolis	0.0457	0.0216	0.0328		0.0354	**0.0411**
9. Formoso do Araguaia	0.0808	0.0359	0.0545			**0.0736**
10. Lagoa da Confusão (1ª Etapa)		0.0301	0.0456		0.0560	**0.0426**
11. Pium (1ª Etapa)	0.0562	0.0266	0.0401		0.0423	**0.0547**
12. Sandolândia	0.0646	0.0310	0.0470	0.0268	0.0577	**0.0525**
13. Santa Rita do Tocantins	0.0666	0.0323	0.0490	0.0240	0.0602	**0.0434**
14. Talismã		0.0349	0.0530	0.0260	0.0651	**0.0467**
PRODOESTE Average	**0.0411**	**0.0284**	**0.0431**	**0.0116**	**0.0398**	**0.0469**
Tocantins Average *	**0.0370**	**0.0291**	**0.0442**	**0.0073**	**0.0395**	**0.0455**
	Sensitivity to Temperature					
1. Aliança do Tocantins	2.1497	1.0553	1.5990	0.7294	1.9658	**1.6533**
2. Alvorada	1.7285	0.8298	1.2585	0.6311	1.4516	**1.4320**
3. Araguaçú	1.4507	0.6859	1.0403		1.1088	**1.3458**
4. Cariri do Tocantins		1.0200	1.5470	0.8534	1.9001	**1.5204**
5. Cristalândia (1ª Etapa)	1.3515	0.6460	0.9798	0.5018	1.1852	**1.2513**
6. Crixás do Tocantins	1.5988	0.6877	1.0430			**1.0938**
7. Dueré	0.0000	0.9540	1.4469			**1.2669**
8. Figueirópolis	1.4475	0.6844	1.0380		1.1221	**1.3002**
9. Formoso do Araguaia	2.5589	1.1383	1.7264			**2.3309**
10. Lagoa da Confusão (1ª Etapa)		0.9525	1.4446		1.7743	**1.3495**
11. Pium (1ª Etapa)	1.7810	0.8421	1.2711		1.3396	**1.7330**
12. Sandolândia	2.0457	0.9815	1.4886	0.8478	1.8284	**1.6640**
13. Santa Rita do Tocantins	2.1089	1.0227	1.5511	0.7606	1.9051	**1.3745**
14. Talismã		1.1063	1.6779	0.8245	2.0608	**1.4804**
PRODOESTE Average	**1.3015**	**0.9005**	**1.3652**	**0.3677**	**1.2601**	**1.4854**
Tocantins Average *	**1.1722**	**0.9229**	**1.3995**	**0.2302**	**1.2522**	**1.4418**

/* This aggregation does not include municipalities where PRODOESTE is operating.

Source: Own estimations.

Table 11. Local vulnerability indicators in agricultural systems. Baseline assessment

Municipalities	Soybeans	Rice	Corn	Watermelon	Beans	Aggregate
	Local Vulnerability to precipitation					
1. Aliança do Tocantins	0.0246	0.0113	0.0172			**0.0191**
2. Alvorada	0.0251	0.0119	0.0180	0.0101	0.0202	**0.0240**
3. Araguaçú	0.0283	0.0138	0.0208	0.0095		**0.0208**
4. Cariri do Tocantins	0.0330	0.0158	0.0240	0.0117	0.0245	**0.0289**
5. Cristalândia (1ª Etapa)	0.0206	0.0090	0.0137	0.0071	0.0139	**0.0113**
6. Crixás do Tocantins	0.0205	0.0097	0.0149	0.0076	0.0156	**0.0159**
7. Dueré	0.0231	0.0101	0.0155	0.0078	0.0165	**0.0135**
8. Figueirópolis	0.0240	0.0113	0.0171	0.0095	0.0184	**0.0218**
9. Formoso do Araguaia	0.0246	0.0115	0.0176	0.0092	0.0215	**0.0148**
10. Lagoa da Confusão (1ª Etapa)	0.0218	0.0102	0.0155	0.0083	0.0190	**0.0132**
11. Pium (1ª Etapa)	0.0219	0.0106	0.0161	0.0106	0.0165	**0.0142**
12. Sandolândia	0.0369	0.0174	0.0264			**0.0244**
13. Santa Rita do Tocantins	0.0296	0.0139	0.0212			**0.0188**
14. Talismã	0.0182	0.0086	0.0130		0.0147	**0.0163**
PRODOESTE Average	**0.0252**	**0.0118**	**0.0179**	**0.0065**	**0.0129**	**0.0184**
Tocantins Average *	**0.0142**	**0.0118**	**0.0179**	**0.0030**	**0.0161**	**0.0185**
	Local Vulnerability to temperature					
1. Aliança do Tocantins	0.5182	0.2361	0.3606			**0.4021**
2. Alvorada	0.0684	0.0323	0.0489	0.0273	0.0538	**0.0654**
3. Araguaçú	0.0779	0.0378	0.0572	0.0272		**0.0573**
4. Cariri do Tocantins	0.0798	0.0383	0.0582	0.0290	0.0610	**0.0702**
5. Cristalândia (1ª Etapa)	0.5081	0.2158	0.3294	0.1718	0.3364	**0.2722**
6. Crixás do Tocantins	0.4793	0.2277	0.3482	0.1781	0.3643	**0.3729**
7. Dueré	0.4248	0.1860	0.2855	0.1432	0.3037	**0.2477**
8. Figueirópolis	0.0658	0.0311	0.0470	0.0260	0.0519	**0.0599**
9. Formoso do Araguaia	0.4109	0.1923	0.2948	0.1547	0.3586	**0.2477**
10. Lagoa da Confusão (1ª Etapa)	0.3766	0.1760	0.2682	0.1430	0.3274	**0.2274**
11. Pium (1ª Etapa)	0.4885	0.2351	0.3593	0.2338	0.3681	**0.3157**
12. Sandolândia	0.2764	0.1230	0.1868			**0.1748**
13. Santa Rita do Tocantins	0.6645	0.3119	0.4764			**0.4235**
14. Talismã	0.0707	0.0334	0.0504		0.0551	**0.0634**
PRODOESTE Average	**0.3221**	**0.1483**	**0.2265**	**0.0810**	**0.1629**	**0.2143**
Tocantins Average *	**0.2317**	**0.1724**	**0.2620**	**0.0474**	**0.2278**	**0.2758**

/* This aggregation does not include municipalities where PRODOESTE is operating.

Source: Own estimations.

Table 12. Aggregate sensitivity indicators for agricultural systems by climate change scenario

Municipalities	Baseline	Medium Term Scenarios				Long Term Scenarios			
					Precipitation				
		B1	**A2**	**B2**	**A1F1**	**B1**	**A2**	**B2**	**A1F1**
1. Aliança do Tocantins	0.0374	0.0415	0.0415	0.0426	0.0438	0.0561	0.0772	0.0611	0.0932
2. Alvorada	0.0424	0.0475	0.0474	0.0488	0.0499	0.0641	0.0878	0.0698	0.1042
3. Araguaçú	0.0367	0.0409	0.0409	0.0421	0.0430	0.0554	0.0766	0.0606	0.0911
4. Cariri do Tocantins	0.0456	0.0502	0.0501	0.0516	0.0528	0.0679	0.0931	0.0740	0.1116
5. Cristalândia (1ª Etapa)	0.0244	0.0265	0.0266	0.0274	0.0281	0.0361	0.0507	0.0398	0.0618
6. Crixás do Tocantins	0.0342	0.0375	0.0375	0.0385	0.0396	0.0508	0.0702	0.0553	0.0849
7. Dueré	0.0228	0.0250	0.0250	0.0257	0.0264	0.0339	0.0465	0.0370	0.0562
8. Figueirópolis	0.0385	0.0432	0.0431	0.0443	0.0453	0.0583	0.0798	0.0635	0.0947
9. Formoso do Araguaia	0.0218	0.0238	0.0238	0.0245	0.0250	0.0320	0.0440	0.0350	0.0526
10. Lagoa da Confusão (1ª Etapa)	0.0202	0.0220	0.0220	0.0226	0.0231	0.0298	0.0417	0.0328	0.0502
11. Pium (1ª Etapa)	0.0275	0.0298	0.0300	0.0308	0.0316	0.0407	0.0575	0.0450	0.0701
12. Sandolândia	0.0391	0.0431	0.0430	0.0443	0.0452	0.0580	0.0795	0.0633	0.0947
13. Santa Rita do Tocantins	0.0372	0.0409	0.0409	0.0421	0.0432	0.0555	0.0772	0.0609	0.0939
14. Talismã	0.0411	0.0462	0.0461	0.0475	0.0485	0.0623	0.0854	0.0680	0.1010
PRODOESTE Average	**0.0335**	**0.0370**	**0.0370**	**0.0381**	**0.0390**	**0.0501**	**0.0691**	**0.0547**	**0.0829**
Tocantins Average *	**0.0470**	**0.0519**	**0.0524**	**0.0542**	**0.0550**	**0.0709**	**0.1012**	**0.0796**	**0.1215**
					Temperature				
	Baseline	**Medium Term Scenarios**				**Long Term Scenarios**			
		B1	**A2**	**B2**	**A1F1**	**B1**	**A2**	**B2**	**A1F1**
1. Aliança do Tocantins	1.1849	1.3153	1.3138	1.3506	1.3884	1.7755	2.4463	1.9359	2.9508
2. Alvorada	1.3413	1.5055	1.5013	1.5448	1.5796	2.0308	2.7816	2.2120	3.3000
3. Araguaçú	1.1617	1.2964	1.2948	1.3327	1.3613	1.7558	2.4258	1.9205	2.8854
4. Cariri do Tocantins	1.4455	1.5913	1.5860	1.6332	1.6729	2.1515	2.9475	2.3442	3.5358
5. Cristalândia (1ª Etapa)	0.7728	0.8398	0.8429	0.8678	0.8906	1.1417	1.6043	1.2612	1.9559
6. Crixás do Tocantins	1.0818	1.1883	1.1872	1.2202	1.2554	1.6074	2.2220	1.7529	2.6901
7. Dueré	0.7210	0.7931	0.7903	0.8145	0.8348	1.0729	1.4716	1.1703	1.7786
8. Figueirópolis	1.2205	1.3679	1.3641	1.4036	1.4353	1.8453	2.5274	2.0099	2.9985
9. Formoso do Araguaia	0.6893	0.7540	0.7532	0.7750	0.7916	1.0149	1.3939	1.1086	1.6646
10. Lagoa da Confusão (1ª Etapa)	0.6411	0.6953	0.6968	0.7167	0.7327	0.9442	1.3194	1.0376	1.5895
11. Pium (1ª Etapa)	0.8721	0.9445	0.9495	0.9768	1.0016	1.2880	1.8224	1.4252	2.2196
12. Sandolândia	1.2386	1.3643	1.3627	1.4021	1.4328	1.8356	2.5178	2.0044	2.9993
13. Santa Rita do Tocantins	1.1784	1.2952	1.2961	1.3341	1.3695	1.7575	2.4464	1.9289	2.9737
14. Talismã	1.3002	1.4637	1.4601	1.5029	1.5348	1.9746	2.7061	2.1526	3.1976
PRODOESTE Average	**1.0606**	**1.1725**	**1.1713**	**1.2054**	**1.2344**	**1.5854**	**2.1880**	**1.7331**	**2.6242**
Tocantins Average *	**1.4894**	**1.6440**	**1.6597**	**1.7152**	**1.7424**	**2.2445**	**3.2058**	**2.5214**	**3.8474**

/* This aggregation does not include municipalities where PRODOESTE is operating.

Source: Own estimations.

Table 13. Local vulnerability to climate change indicators for agricultural systems

Municipalities	Baseline	Medium Term Scenarios				Long Term Scenarios			
					Precipitation				
		B1	A2	B2	A1F1	B1	A2	B2	A1F1
1. Aliança do Tocantins	0.0268	0.0281	0.0285	0.0292	0.0293	0.0357	0.0476	0.0394	0.0540
2. Alvorada	0.0126	0.0133	0.0133	0.0136	0.0138	0.0167	0.0216	0.0179	0.0244
3. Araguaçú	0.0213	0.0224	0.0225	0.0230	0.0235	0.0283	0.0371	0.0305	0.0430
4. Cariri do Tocantins	0.0164	0.0173	0.0175	0.0179	0.0180	0.0219	0.0292	0.0241	0.0332
5. Cristalândia (1ª Etapa)	0.0214	0.0226	0.0227	0.0231	0.0235	0.0285	0.0368	0.0305	0.0417
6. Crixás do Tocantins	0.0152	0.0162	0.0162	0.0165	0.0170	0.0206	0.0267	0.0219	0.0308
7. Dueré	0.0147	0.0155	0.0155	0.0158	0.0162	0.0195	0.0254	0.0209	0.0287
8. Figueirópolis	0.0163	0.0175	0.0175	0.0178	0.0181	0.0221	0.0286	0.0236	0.0322
9. Formoso do Araguaia	0.0293	0.0310	0.0313	0.0319	0.0326	0.0392	0.0518	0.0425	0.0603
10. Lagoa da Confusão (1ª Etapa)	0.0127	0.0133	0.0135	0.0139	0.0139	0.0170	0.0227	0.0188	0.0257
11. Pium (1ª Etapa)	0.0204	0.0212	0.0214	0.0218	0.0223	0.0270	0.0359	0.0294	0.0419
12. Sandolândia	0.0202	0.0212	0.0215	0.0220	0.0223	0.0271	0.0367	0.0300	0.0426
13. Santa Rita do Tocantins	0.0187	0.0197	0.0200	0.0205	0.0207	0.0254	0.0347	0.0284	0.0404
14. Talismã	0.0198	0.0208	0.0211	0.0217	0.0219	0.0268	0.0366	0.0299	0.0424
PRODOESTE Average	**0.0190**	**0.0200**	**0.0202**	**0.0206**	**0.0209**	**0.0254**	**0.0337**	**0.0277**	**0.0387**
Tocantins Average *	**0.0184**	**0.0194**	**0.0196**	**0.0200**	**0.0203**	**0.0247**	**0.0329**	**0.0270**	**0.0380**
					Temperature				
	Baseline	**Medium Term Scenarios**				**Long Term Scenarios**			
		B1	A2	B2	A1F1	B1	A2	B2	A1F1
1. Aliança do Tocantins	0.6885	0.7231	0.7321	0.7518	0.7530	0.9174	1.2231	1.0141	1.3886
2. Alvorada	0.2789	0.2944	0.2953	0.3008	0.3064	0.3706	0.4802	0.3975	0.5426
3. Araguaçú	0.0658	0.0692	0.0697	0.0710	0.0726	0.0873	0.1146	0.0943	0.1329
4. Cariri do Tocantins	0.1977	0.2080	0.2105	0.2158	0.2165	0.2641	0.3520	0.2908	0.3994
5. Cristalândia (1ª Etapa)	0.3067	0.3242	0.3246	0.3307	0.3368	0.4081	0.5262	0.4360	0.5970
6. Crixás do Tocantins	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
7. Dueré	0.0617	0.0651	0.0653	0.0665	0.0679	0.0820	0.1068	0.0881	0.1205
8. Figueirópolis	0.0634	0.0679	0.0679	0.0692	0.0703	0.0858	0.1110	0.0918	0.1251
9. Formoso do Araguaia	0.8173	0.8644	0.8721	0.8881	0.9081	1.0927	1.4446	1.1848	1.6817
10. Lagoa da Confusão (1ª Etapa)	0.1752	0.1842	0.1864	0.1915	0.1919	0.2346	0.3135	0.2594	0.3551
11. Pium (1ª Etapa)	0.7351	0.7657	0.7730	0.7883	0.8040	0.9741	1.2969	1.0603	1.5121
12. Sandolândia	0.6248	0.6557	0.6646	0.6806	0.6894	0.8400	1.1370	0.9279	1.3212
13. Santa Rita do Tocantins	0.1780	0.1867	0.1896	0.1950	0.1966	0.2408	0.3297	0.2693	0.3838
14. Talismã	0.1924	0.2021	0.2053	0.2112	0.2126	0.2603	0.3561	0.2914	0.4131
PRODOESTE Average	**0.3133**	**0.3293**	**0.3326**	**0.3400**	**0.3447**	**0.4184**	**0.5565**	**0.4575**	**0.6409**
Tocantins Average *	**0.2647**	**0.2774**	**0.2802**	**0.2862**	**0.2910**	**0.3531**	**0.4708**	**0.3857**	**0.5453**

/* This aggregation does not include municipalities where PRODOESTE is operating.

Source: Own estimations.

Table 14. Adaptive Capacity Assessment Based on Irrigation Conditions, Climate Change Assessment

Variable	Horizon	Scenario	Mean	Std. Dev.	Min	Max
Precipitation	Medium-Term	A1F1	0.003	0.006	-0.007	0.029
		A2	0.003	0.006	-0.006	0.029
		B1	0.003	0.006	-0.006	0.029
		B2	0.003	0.006	-0.007	0.031
	Long-Term	A1F1	-0.014	0.016	-0.065	0.038
		A2	-0.008	0.013	-0.043	0.040
		B1	0.000	0.008	-0.015	0.035
		B2	-0.001	0.009	-0.019	0.039
Temperature	Medium-Term	A1F1	-0.328	0.339	-1.970	0.022
		A2	-0.298	0.311	-1.812	0.028
		B1	-0.291	0.305	-1.784	0.030
		B2	-0.315	0.326	-1.887	0.025
	Long-Term	A1F1	-1.206	1.141	-6.301	0.000
		A2	-0.929	0.879	-4.890	0.000
		B1	-0.526	0.517	-2.936	0.000
		B2	-0.629	0.607	-3.408	0.000

Source: Own estimations.

Table 15. Econometric Model to Estimate Stressors Effects on Yields in Tocantins. Four Crops: Rice, Beans, Watermelon, Corn and Soybeans.

Variable	Estimator	Std. Err.	t	P>t	Variable	Estimator	Std. Err.	t	P>t
Log Precipitation, season 1	0.007	0.015	0.450	0.656	Dummy Municipality 71	-0.088	0.028	-3.160	0.002
Log Precipitation, season 2	0.091	0.018	5.130	0.000	Dummy Municipality 72	0.127	0.020	6.360	0.000
Log Precipitation, season 3	0.099	0.022	4.510	0.000	Dummy Municipality 73	0.085	0.005	18.420	0.000
Log Precipitation, season 4	-0.016	0.011	-1.510	0.134	Dummy Municipality 74	0.779	0.058	13.370	0.000
Log Temperature, season 1	3.380	0.577	5.860	0.000	Dummy Municipality 75	0.043	0.020	2.190	0.030
Log Temperature, season 2	2.212	0.785	2.820	0.006	Dummy Municipality 76	0.047	0.009	5.300	0.000
Log Temperature, season 3	-0.443	0.805	-0.550	0.583	Dummy Municipality 77	0.123	0.007	16.540	0.000
Log Temperature, season 4	0.573	0.644	0.890	0.375	Dummy Municipality 78	0.353	0.017	20.340	0.000
Trend	0.013	0.004	3.240	0.002	Dummy Municipality 79	0.059	0.005	11.760	0.000
Dummy Rice	-2.500	0.058	-42.860	0.000	Dummy Municipality 80	0.040	0.018	2.250	0.026
Dummy Beans	-3.530	0.063	-55.670	0.000	Dummy Municipality 81	0.397	0.039	10.140	0.000
Dummy Corn	-2.351	0.057	-41.350	0.000	Dummy Municipality 82	0.062	0.020	3.110	0.002
Dummy Soybeans	-2.131	0.053	-40.290	0.000	Dummy Municipality 83	0.085	0.016	5.160	0.000
Dummy Municipality 2	0.077	0.017	4.460	0.000	Dummy Municipality 84	0.069	0.011	6.170	0.000
Dummy Municipality 3	0.388	0.012	33.440	0.000	Dummy Municipality 85	0.191	0.022	8.820	0.000
Dummy Municipality 4	0.582	0.051	11.330	0.000	Dummy Municipality 86	0.581	0.052	11.240	0.000
Dummy Municipality 5	0.537	0.026	20.680	0.000	Dummy Municipality 87	0.467	0.061	7.630	0.000
Dummy Municipality 6	-0.019	0.018	-1.070	0.285	Dummy Municipality 88	0.049	0.011	4.540	0.000
Dummy Municipality 7	-0.010	0.018	-0.550	0.584	Dummy Municipality 89	0.543	0.012	44.290	0.000
Dummy Municipality 8	0.180	0.010	17.570	0.000	Dummy Municipality 90	0.000	0.010	-0.010	0.994
Dummy Municipality 9	0.037	0.019	2.010	0.046	Dummy Municipality 91	0.107	0.016	6.670	0.000
Dummy Municipality 10	0.055	0.007	8.110	0.000	Dummy Municipality 92	0.402	0.033	12.110	0.000
Dummy Municipality 11	0.447	0.036	12.390	0.000	Dummy Municipality 93	0.126	0.009	13.670	0.000
Dummy Municipality 12	0.232	0.021	11.160	0.000	Dummy Municipality 94	0.224	0.036	6.230	0.000
Dummy Municipality 13	-0.001	0.016	-0.030	0.974	Dummy Municipality 95	0.070	0.017	4.060	0.000
Dummy Municipality 14	0.034	0.023	1.450	0.150	Dummy Municipality 96	0.509	0.008	60.060	0.000
Dummy Municipality 15	0.130	0.015	8.400	0.000	Dummy Municipality 97	0.283	0.017	16.540	0.000
Dummy Municipality 16	0.519	0.046	11.330	0.000	Dummy Municipality 98	0.119	0.016	7.330	0.000
Dummy Municipality 17	0.063	0.021	3.020	0.003	Dummy Municipality 99	0.567	0.044	12.850	0.000
Dummy Municipality 18	0.633	0.071	8.960	0.000	Dummy Municipality 100	0.036	0.018	2.060	0.041
Dummy Municipality 19	0.052	0.019	2.720	0.007	Dummy Municipality 101	0.449	0.008	54.180	0.000
Dummy Municipality 20	0.075	0.012	6.000	0.000	Dummy Municipality 102	0.562	0.075	7.510	0.000
Dummy Municipality 21	0.135	0.020	6.830	0.000	Dummy Municipality 103	0.320	0.032	10.100	0.000
Dummy Municipality 22	0.093	0.010	9.050	0.000	Dummy Municipality 104	0.492	0.051	9.560	0.000
Dummy Municipality 23	0.079	0.007	10.980	0.000	Dummy Municipality 105	0.486	0.014	35.770	0.000
Dummy Municipality 24	0.069	0.018	3.970	0.000	Dummy Municipality 106	0.038	0.022	1.710	0.090
Dummy Municipality 25	0.344	0.009	40.420	0.000	Dummy Municipality 107	0.098	0.012	8.050	0.000
Dummy Municipality 26	0.084	0.012	6.750	0.000	Dummy Municipality 108	0.179	0.009	19.110	0.000
Dummy Municipality 27	0.316	0.012	25.860	0.000	Dummy Municipality 109	0.173	0.033	5.200	0.000
Dummy Municipality 28	-0.073	0.031	-2.380	0.019	Dummy Municipality 110	-0.018	0.016	-1.110	0.269
Dummy Municipality 29	0.091	0.020	4.560	0.000	Dummy Municipality 111	0.376	0.065	5.740	0.000
Dummy Municipality 30	0.420	0.028	14.950	0.000	Dummy Municipality 112	-0.048	0.010	-4.760	0.000
Dummy Municipality 31	0.350	0.023	15.540	0.000	Dummy Municipality 113	-0.018	0.012	-1.480	0.141
Dummy Municipality 32	0.045	0.021	2.160	0.033	Dummy Municipality 114	-0.048	0.024	-1.950	0.053
Dummy Municipality 33	0.030	0.025	1.180	0.239	Dummy Municipality 115	0.186	0.014	13.160	0.000
Dummy Municipality 34	0.072	0.008	8.720	0.000	Dummy Municipality 116	0.119	0.020	5.850	0.000
Dummy Municipality 35	0.104	0.015	6.940	0.000	Dummy Municipality 117	0.111	0.012	9.610	0.000
Dummy Municipality 36	0.326	0.029	11.320	0.000	Dummy Municipality 118	0.156	0.010	14.980	0.000
Dummy Municipality 37	-0.047	0.006	-7.380	0.000	Dummy Municipality 119	0.379	0.024	15.630	0.000
Dummy Municipality 38	0.154	0.013	11.420	0.000	Dummy Municipality 120	0.030	0.011	2.680	0.008
Dummy Municipality 39	0.068	0.019	3.620	0.000	Dummy Municipality 121	0.145	0.019	7.750	0.000
Dummy Municipality 40	0.862	0.090	9.540	0.000	Dummy Municipality 122	0.089	0.017	5.310	0.000
Dummy Municipality 41	0.275	0.041	6.710	0.000	Dummy Municipality 123	0.094	0.044	2.110	0.037
Dummy Municipality 42	0.073	0.012	5.990	0.000	Dummy Municipality 124	0.061	0.022	2.750	0.007
Dummy Municipality 43	0.506	0.013	38.230	0.000	Dummy Municipality 125	0.169	0.024	7.010	0.000
Dummy Municipality 44	0.442	0.015	29.960	0.000	Dummy Municipality 126	-0.110	0.030	-3.620	0.000
Dummy Municipality 45	0.219	0.015	14.950	0.000	Dummy Municipality 127	0.292	0.023	12.630	0.000
Dummy Municipality 46	0.693	0.058	12.000	0.000	Dummy Municipality 128	0.510	0.024	20.880	0.000
Dummy Municipality 47	-0.010	0.003	-3.220	0.002	Dummy Municipality 129	0.056	0.019	2.920	0.004
Dummy Municipality 48	0.041	0.004	10.090	0.000	Dummy Municipality 130	0.499	0.017	28.950	0.000
Dummy Municipality 49	0.646	0.013	49.500	0.000	Dummy Municipality 131	0.745	0.070	10.720	0.000
Dummy Municipality 50	-0.014	0.028	-0.520	0.606	Dummy Municipality 132	0.266	0.044	6.060	0.000
Dummy Municipality 51	0.201	0.011	18.970	0.000	Dummy Municipality 133	0.520	0.029	18.130	0.000
Dummy Municipality 52	0.583	0.026	22.470	0.000	Dummy Municipality 134	-0.107	0.007	-14.450	0.000
Dummy Municipality 53	0.040	0.014	2.770	0.006	Dummy Municipality 135	0.132	0.020	6.720	0.000
Dummy Municipality 54	0.628	0.017	36.050	0.000	Dummy Municipality 136	0.183	0.010	18.490	0.000
Dummy Municipality 55	0.089	0.007	12.090	0.000	Dummy Municipality 137	0.043	0.009	4.620	0.000
Dummy Municipality 56	0.114	0.012	9.470	0.000	Dummy Municipality 138	0.079	0.015	5.200	0.000
Dummy Municipality 57	0.137	0.011	12.580	0.000	Dummy Municipality 139	-0.019	0.015	-1.270	0.204
Dummy Municipality 58	0.161	0.012	13.080	0.000	Dummy year 2	-0.098	0.021	-4.730	0.000
Dummy Municipality 59	0.385	0.015	26.450	0.000	Dummy year 3	0.059	0.022	2.710	0.008
Dummy Municipality 60	0.220	0.013	16.560	0.000	Dummy year 4	-0.009	0.015	-0.630	0.532
Dummy Municipality 61	0.122	0.015	8.140	0.000	Dummy year 5	0.096	0.031	3.140	0.002
Dummy Municipality 62	0.016	0.021	0.760	0.448	Dummy year 6	0.064	0.025	2.510	0.013
Dummy Municipality 63	0.061	0.009	6.820	0.000	Dummy year 7	-0.050	0.026	-1.910	0.058
Dummy Municipality 64	0.156	0.024	6.560	0.000	Dummy year 8	-0.056	0.020	-2.810	0.006
Dummy Municipality 65	0.263	0.032	8.090	0.000	Dummy year 9	0.068	0.028	2.420	0.017
Dummy Municipality 66	0.018	0.018	1.040	0.302	Dummy year 10	0.046	0.028	1.680	0.096
Dummy Municipality 67	0.681	0.016	42.250	0.000	Dummy year 11	-0.010	0.023	-0.440	0.658
Dummy Municipality 68	0.051	0.016	3.290	0.001	_cons	-17.359	3.267	-5.310	0.000
Dummy Municipality 69	-0.116	0.009	-12.630	0.000					
Dummy Municipality 70	0.511	0.071	7.240	0.000					

Table 16. High Irrigation. Econometric Model to Estimate Stressors Effects on Yields in Tocantins. Four Crops: Rice, Beans, Watermelon, Corn and Soybeans.

Variable	Estimator	Std. Err.	t	P>t
Log. accum. precipitation Oct-Nov	-0.015	0.037	-0.410	0.681
Log. accum. precipitation Dec-Jan	0.054	0.036	1.490	0.145
Log. accum. precipitation Feb-Mar	0.179	0.037	4.900	0.000
Log. accum. precipitation Apr-May	-0.026	0.021	-1.270	0.212
Log. average temperature Oct-Nov	2.622	1.185	2.210	0.034
Log. average temperature Dec-Jan	1.848	1.551	1.190	0.242
Log. average temperature Feb-Mar	1.424	1.328	1.070	0.291
Log. average temperature Apr-May	-1.613	1.201	-1.340	0.188
Dummy years	0.019	0.009	2.090	0.045
Dummy crop rice	-0.343	0.069	-4.950	0.000
Dummy crop corn	-1.245	0.097	-12.860	0.000
Dummy crop watermelon	2.165	0.079	27.240	0.000
Dummy crop beans	-0.195	0.064	-3.050	0.004
Dummy month, January	0.054	0.039	1.380	0.178
Dummy month, February	-0.057	0.046	-1.220	0.229
Dummy month, March	0.164	0.053	3.100	0.004
Dummy month, April	0.065	0.034	1.900	0.066
Dummy month, May	0.128	0.070	1.820	0.078
Dummy month, June	0.091	0.057	1.600	0.119
Dummy month, July	0.021	0.048	0.430	0.671
Dummy month, August	-0.015	0.048	-0.320	0.753
Dummy month, September	0.117	0.052	2.260	0.030
Dummy month, October	0.084	0.050	1.680	0.103
Dummy month, November	0.055	0.030	1.800	0.080
Constant	-0.059	0.031	-1.930	0.062

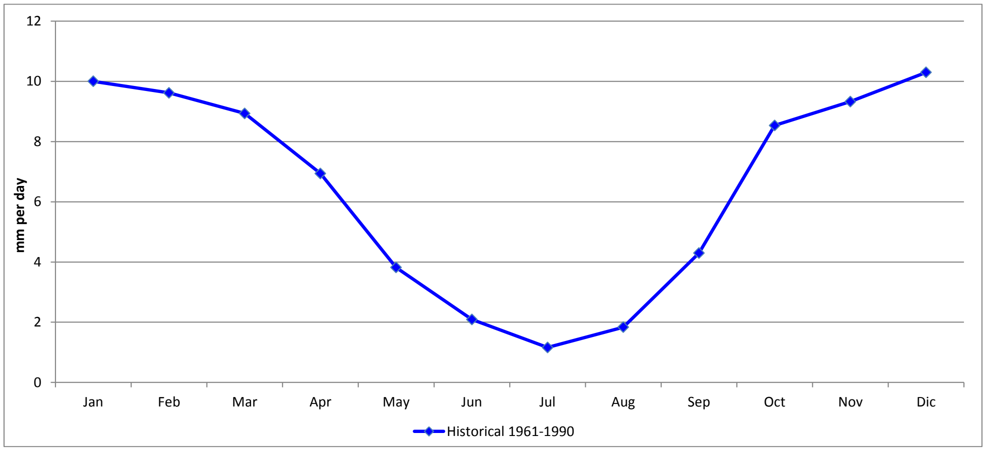
Table 17. Low Irrigation. Econometric Model to Estimate Stressors Effects on Yields in Tocantins. Four Crops: Rice, Beans, Watermelon, Corn and Soybeans.

Variable	Estimator	Std. Err.	t	P>t
Log. accum. precipitation Oct-Nov	0.017	0.016	1.070	0.289
Log. accum. precipitation Dec-Jan	0.101	0.021	4.800	0.000
Log. accum. precipitation Feb-Mar	0.067	0.025	2.740	0.007
Log. accum. precipitation Apr-May	-0.016	0.013	-1.230	0.220
Log. average temperature Oct-Nov	3.562	0.588	6.050	0.000
Log. average temperature Dec-Jan	2.220	0.888	2.500	0.014
Log. average temperature Feb-Mar	-1.000	0.919	-1.090	0.279
Log. average temperature Apr-May	1.207	0.707	1.710	0.091
Dummy years	0.014	0.004	3.850	0.000
Dummy crop rice	-0.377	0.027	-13.740	0.000
Dummy crop corn	-1.459	0.045	-32.780	0.000
Dummy crop watermelon	2.149	0.054	40.130	0.000
Dummy crop beans	-0.227	0.033	-6.960	0.000
Dummy month, January	0.016	0.030	0.540	0.591
Dummy month, February	-0.078	0.026	-3.030	0.003
Dummy month, March	0.045	0.028	1.630	0.106
Dummy month, April	-0.009	0.025	-0.360	0.720
Dummy month, May	0.100	0.035	2.890	0.005
Dummy month, June	0.072	0.030	2.420	0.017
Dummy month, July	-0.059	0.038	-1.570	0.119
Dummy month, August	-0.056	0.027	-2.080	0.040
Dummy month, September	0.060	0.036	1.680	0.097
Dummy month, October	0.040	0.037	1.090	0.280
Dummy month, November	-0.029	0.031	-0.930	0.353
Constant	-0.009	0.022	-0.400	0.691

11.Figure Annex

Figure 1. Precipitation cycle in the Tocantins basin, Brazil

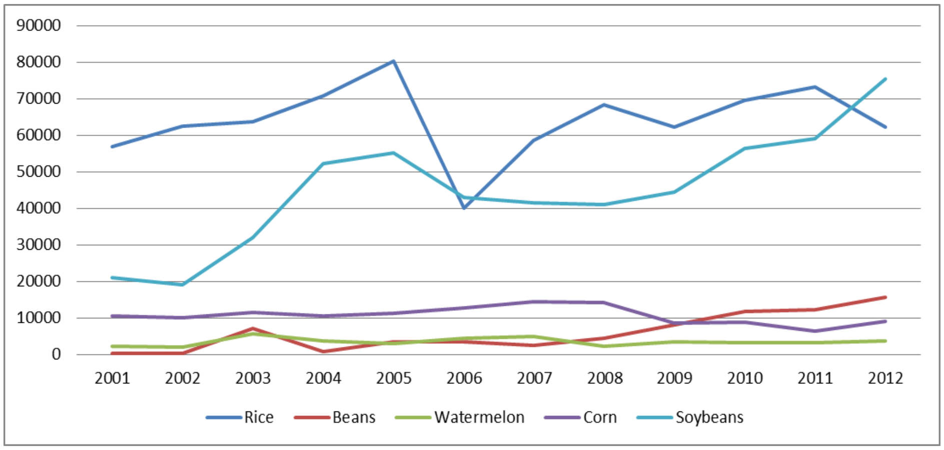
Average historical data 1961-1990



Source: World Bank, Climate Change Knowledge Portal

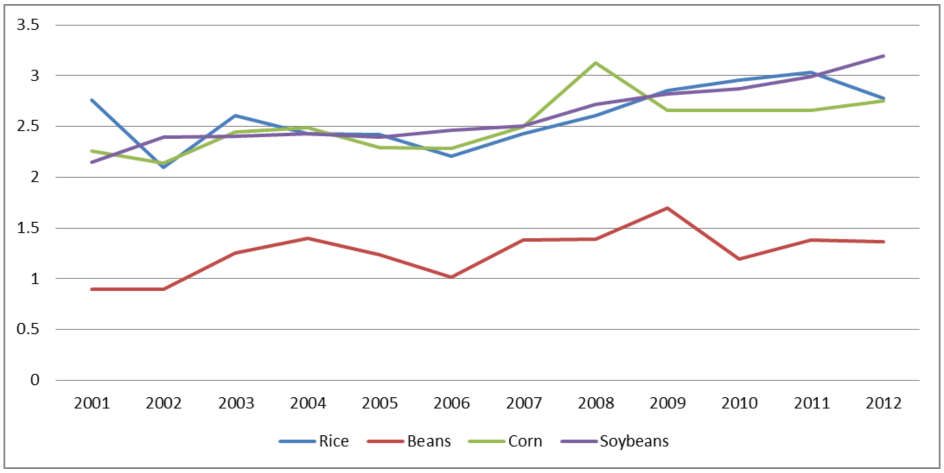
Figure 2. State of Tocantins and municipalities with PRODOESTE

Figure 3. Cultivated area of main crops in PRODOESTE's municipalities (ha)



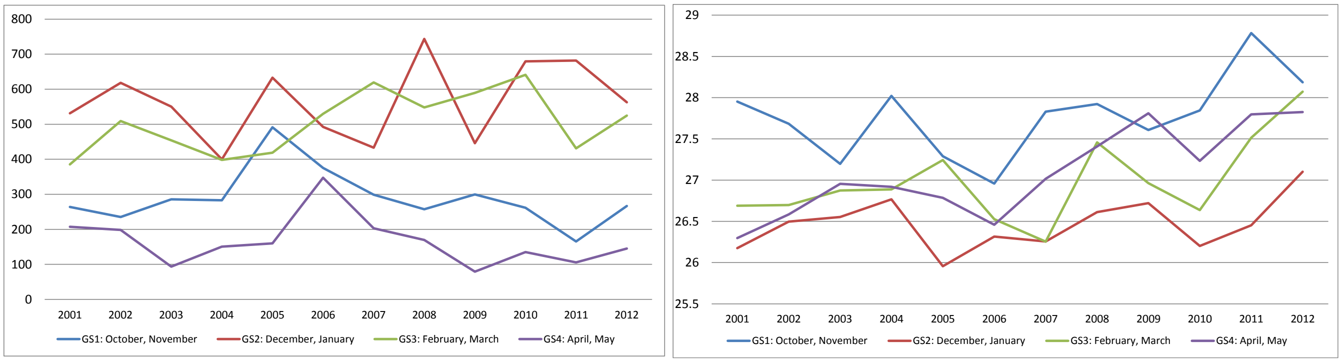
Source: IBGE

Figure 4. Yields of main crops in PRODOESTE's municipalities (Ton/ha)



Source: IBG

Figure 5. Historical average climate variables for Tocantins



a) Accumulated precipitation (mm)

b) Average temperature (°C)

Source: Own estimations with data from the Climate Research Unit of the University of East Anglia.

Figure 6. Precipitation vulnerability indicators for Tocantins and PRODOESTE's municipalities

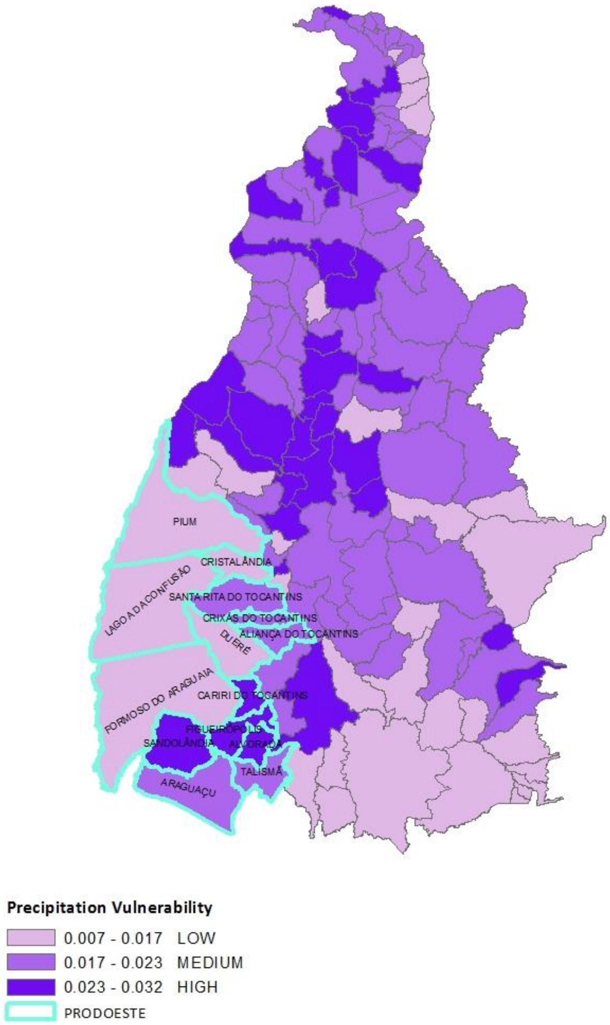


Figure 7. Temperature vulnerability indicators for

Tocantins and PRODOESTE's municipalities

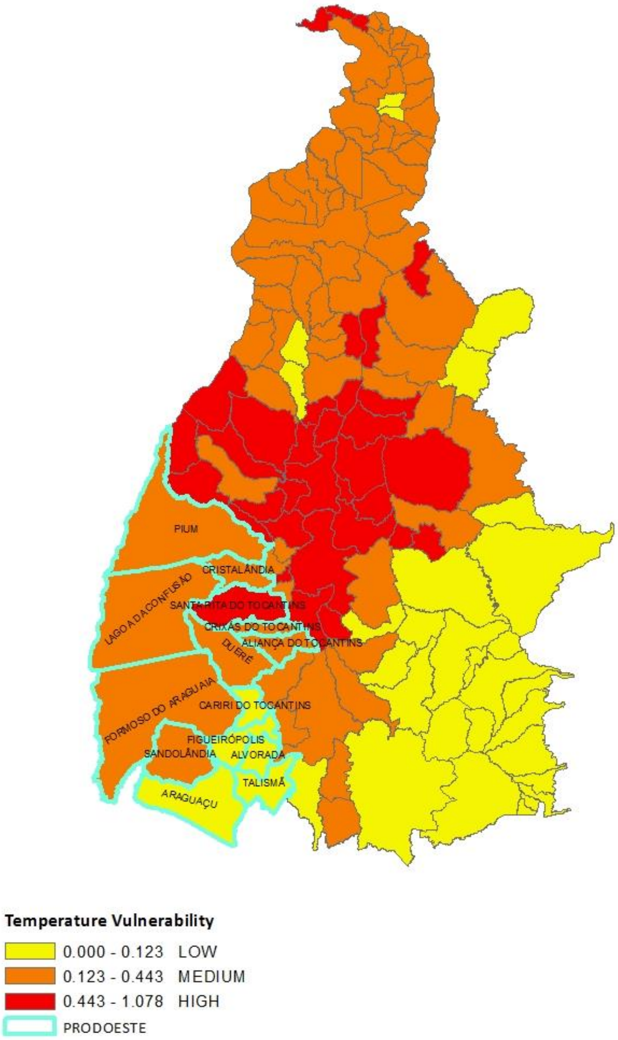


Figure 8. Differences in precipitation vulnerability in the medium-term: Baseline-A1F1 climate change scenario

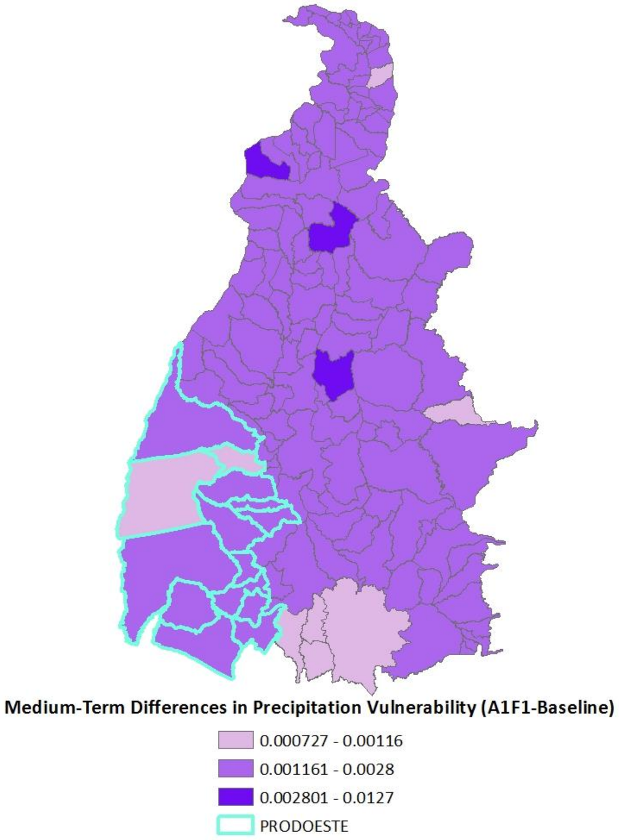


Figure 9. Differences in temperature vulnerability in the medium-term: Baseline-A1F1 climate change scenario