Four commodity crops account for 75% of calories consumed by humans
- Maize (corn), wheat, rice and soybeans
- United States produces 23% of those calories
- Global market share of US corn > 40%

**Statistical analysis**
- Panel of county-level yields in Eastern United States
- Corn and Soybeans (two biggest staple commodities in US)
- Fine-scale weather (daily temperature / precip on 2.5mile grid)
- Years: 1950-2005

**Model accounts for**
- Amount of time spent in each 1°C interval
- Quadratic in total precipitation
- State-specific quadratic time trends
- County fixed effects
Results: Effect of Temperature on Yields

Panel of Corn and Soybean Yields

Schlenker & Roberts (PNAS 2009)
Construction of Degree Days

[Graph showing the construction of degree days, with axes labeled as follows:

- \( T_{max} \)
- \( T_{avg} \)
- \( T_{min} \)

The graph illustrates the relationship between maximum, average, and minimum temperatures, highlighting the concept of degree days.]
Results for Various Sources of Variation

Cross-section versus Panel versus Time Series

Schlenker & Roberts (PNAS 2009)
Recent Example: 2012 Heat Wave / Drought

Berry, Roberts & Schlenker (2013)
Recent Example: 2012 Heat Wave / Drought

Coefficient Over Growing Season (0: Planting / 1: Harvest)

5 Spline Knots

Berry, Roberts & Schlenker (2013)
Allowing for Interactions that Can Evolve Over Season

<table>
<thead>
<tr>
<th></th>
<th>(1)</th>
<th>(2)</th>
<th>(3)</th>
<th>(4)</th>
<th>(5)</th>
<th>(6)</th>
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</thead>
<tbody>
<tr>
<td>Thousand Degree Days 10-29°C</td>
<td>0.333***</td>
<td>0.354***</td>
<td>0.334***</td>
<td>0.336***</td>
<td>0.313***</td>
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<tr>
<td></td>
<td>(0.091)</td>
<td>(0.075)</td>
<td>(0.074)</td>
<td>(0.072)</td>
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<tr>
<td>Hundred Degree Days Above 29°C</td>
<td>-0.591***</td>
<td>-0.562***</td>
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<td>(0.086)</td>
<td>(0.107)</td>
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<tr>
<td>DDays Above 29°C X Precipitation</td>
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<td>-32.435</td>
<td>-19.560</td>
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<tr>
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<td>(31.586)</td>
<td>(25.565)</td>
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<tr>
<td>Precipitation (m)</td>
<td>0.649***</td>
<td>0.708***</td>
<td>0.650***</td>
<td>0.654***</td>
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<tr>
<td></td>
<td>(0.211)</td>
<td>(0.207)</td>
<td>(0.231)</td>
<td>(0.237)</td>
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<tr>
<td>Precipitation (m) Squared</td>
<td>-0.439**</td>
<td>-0.473***</td>
<td>-0.409**</td>
<td>-0.415**</td>
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<tr>
<td></td>
<td>(0.166)</td>
<td>(0.160)</td>
<td>(0.170)</td>
<td>(0.173)</td>
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</tbody>
</table>

Panel A: Time Invariant Variables

Panel B: Joint Significance of Time Varying Variable

Panel C: Impact of 2012 Weather Outcome

<table>
<thead>
<tr>
<th></th>
<th>Total Production Impact (%)</th>
<th>RMSE - 2012 County Prediction</th>
<th>Pred. Error Total Prod 2012 (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-18.54</td>
<td>0.3688</td>
<td>8.00</td>
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<td>-18.78</td>
<td>0.3672</td>
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<td>-20.79</td>
<td>0.3329</td>
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<td>-20.73</td>
<td>0.3285</td>
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<tr>
<td></td>
<td>-22.19</td>
<td>0.3328</td>
<td>2.96</td>
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<td></td>
<td>-22.80</td>
<td>0.3271</td>
<td>1.69</td>
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</tbody>
</table>

Panel D: Prediction Error for 2012

R² | Observations | Counties | Spline Knots (Time Varying Var.) |
---|--------------|----------|---------------------------------|
0.5151 | 43249 | 1659 | 5 |
0.5167 | 43249 | 1659 | 5 |
0.5370 | 43249 | 1659 | 5 |
0.5407 | 43249 | 1659 | 5 |
0.5524 | 43249 | 1659 | 5 |
0.5540 | 43249 | 1659 | 5 |
Outline

1. Modeling US Yields
2. Water versus Temperature
3. Adaptation to Extreme Heat
4. Adaptation to Production Variability
5. Conclusions
Agronomic Evidence on Mechanism

- **Biophysical evidence**
    - APSIM: biophysical model of crop growth
    - Includes water balance, etc

- **Mechanism behind EDD (extreme heat)**
  - Impacts water stress in two ways
    - Reducing soil water (evaporation)
    - Increased demand for soil water to sustain carbon uptake
  - Precipitation only impacts soil moisture

- **Drought is a relative concept**
  - Water requirements depend on temperature
Outline

1 Modeling US Yields
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Adaptation to Extreme Heat

- Tremendous progress in average yields (3-fold increase since 1950)

- No improvement in sensitivity to extreme heat
  - Crops as sensitive in 2010 as in 1950
  - Cross-section gives comparable result to time series

- Possible impediment to adaptation: subsidized crop insurance
  - Farmers don’t have full incentive to deal with extreme
  - They will be bailed out to some extend

- Thought experiment (Butler and Huybers, 2013)
  - Are hotter places less sensitive to extreme heat?
  - Can we assume that with climate change places will adapt?
    - Places that are currently cold will reduce sensitivity when they warm
    - But is reduction in sensitivity costless?
Adaption to Extreme Heat: Changing Sensitivity

Schlenker, Roberts, and Lobell (2013)
Linear Interpolation: Cold County Becomes Hot

Schlenker, Roberts, and Lobell (2013)
Modeling the Benefit of Adaptation

Schlenker, Roberts, and Lobell (2013)

Schlenker, Roberts, and Lobell (2013)
Benefit and Cost of Adaptation

Schlenker, Roberts, and Lobell (2013)
### Impacts of 2°C Warming

<table>
<thead>
<tr>
<th></th>
<th>Mean (1a)</th>
<th>Impact Among 1829 Counties (1b)</th>
<th>Max (1c)</th>
<th>Losers (1d)</th>
<th>Gainers (1e)</th>
<th>Weighted Impact (2)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Panel A: Model using Log Yields as Dependent Variable</strong></td>
<td></td>
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<tr>
<td>Reference Model</td>
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<tr>
<td>Constant Effect of Heat</td>
<td>-16.5%</td>
<td>-67.6%</td>
<td>14.2%</td>
<td>1610</td>
<td>219</td>
<td>-10.7%</td>
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<td>Sensitivity to Heat Varies (Model 2)</td>
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<td></td>
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<tr>
<td>Impact without Adaptation</td>
<td>-17.3%</td>
<td>-38.6%</td>
<td>14.8%</td>
<td>1765</td>
<td>64</td>
<td>-14.9%</td>
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<tr>
<td>Impact with Adaptation</td>
<td>-8.7%</td>
<td>-20.4%</td>
<td>16.1%</td>
<td>1665</td>
<td>164</td>
<td>-7.6%</td>
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<tr>
<td>Robustness vs Average Yield</td>
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<tr>
<td>Costly Adaptation</td>
<td>-12.5%</td>
<td>-28.8%</td>
<td>15.7%</td>
<td>1717</td>
<td>112</td>
<td>-10.9%</td>
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<tr>
<td><strong>Panel B: Model using Yields as Dependent Variable</strong></td>
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<td>Reference Model</td>
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<tr>
<td>Constant Effect of Heat</td>
<td>-18.2%</td>
<td>-184.8%</td>
<td>15.9%</td>
<td>1551</td>
<td>278</td>
<td>-7.4%</td>
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<td>Sensitivity to Heat Varies (Model 2)</td>
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<tr>
<td>Impact without Adaptation</td>
<td>-16.0%</td>
<td>-147.7%</td>
<td>16.7%</td>
<td>1773</td>
<td>56</td>
<td>-10.8%</td>
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<td>-3.9%</td>
<td>-35.2%</td>
<td>63.2%</td>
<td>1557</td>
<td>272</td>
<td>-3.7%</td>
</tr>
<tr>
<td>Robustness vs Average Yield</td>
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<tr>
<td>Costly Adaptation</td>
<td>-9.2%</td>
<td>-83.7%</td>
<td>40.7%</td>
<td>1693</td>
<td>136</td>
<td>-6.8%</td>
</tr>
</tbody>
</table>
Outline

1. Modeling US Yields
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Yield Variability in the Future

- Highly nonlinear relationship between yields and temperature
- Increase in mean temperature
  - Reduction in average yields
    - Increase in frequency of extreme heat
  - Increase in yield variability
    - Even if weather variability does not change
    - Relationship between yields and weather have higher curvature
    - Same weather fluctuation result in larger yield swings

- Will food prices become more variable?
  - Calibrate a storage model
  - Storage driven by arbitrage between periods
    - If production more variable, incentive to hold more stock
    - Higher stock levels: higher average price as storage costly, but less variability
Adaptation: Storage can Smooth Variability

Graphs showing:
- Mean yield (people/hectare/year) with different scenarios:
  - No yield change (year 2000)
  - Yield trend and CV change
  - Yield trend changes
  - Yield CV changes
- Yield SD (people/hectare/year)
- Mean price (dollars/person/year)
- Price CV
- Mean Inventory (billion people)
Adaptation: Storage can Smooth Variability

- No storage adaptation: -71% change
- Storage adaptation without anticipation: 87% change
- Storage adaptation with anticipation: 94% change

Legend:
- Price
- Price CV
- Inventory
Outline

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Conclusions

- Statistical study linking yields and weather
  - Driving force: extreme heat
  - Large yield decline if maximum temperature rises a lot
  - Potential offsetting benefits of CO₂

- Agronomic evidence
  - APSIM model
  - Extreme heat has larger effects on yields than precipitation

- Adapting to extreme heat
  - Seems costly and first-order effect likely to be small
    - Consistent with envelope theorem
    - Farmers maximized their production process
    - First-order adaptation effects are zero
  - Disincentives for adaptation due to crop insurance
  - Most likely is shift in growing area

- Variability of production
  - Adaptation fairly easy through storage