地球規模の食料生産予測

Evaluating the productivities of major crops at the global scale using process-based crop model

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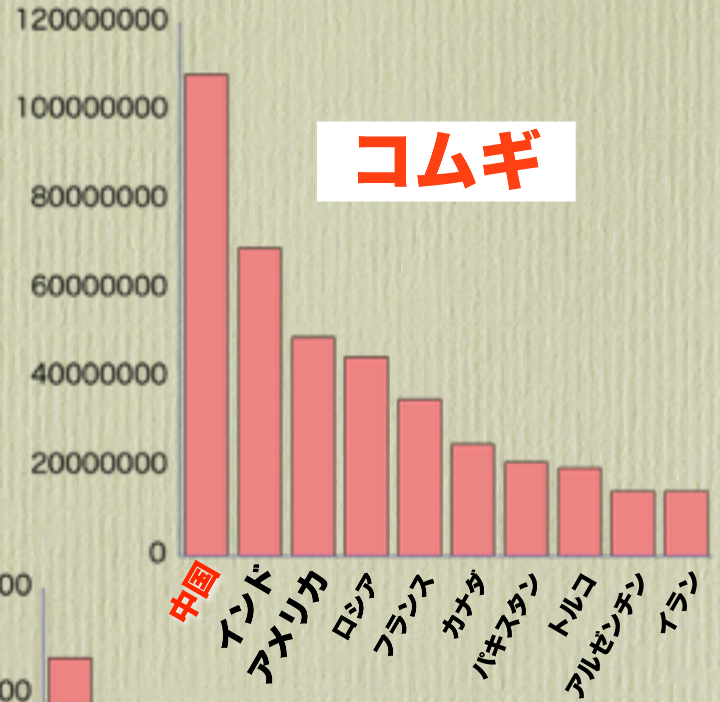
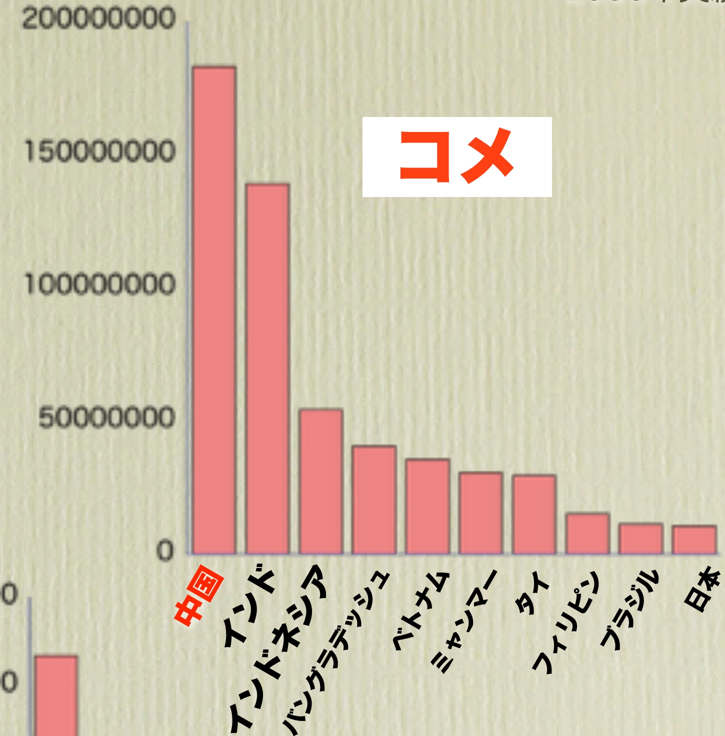
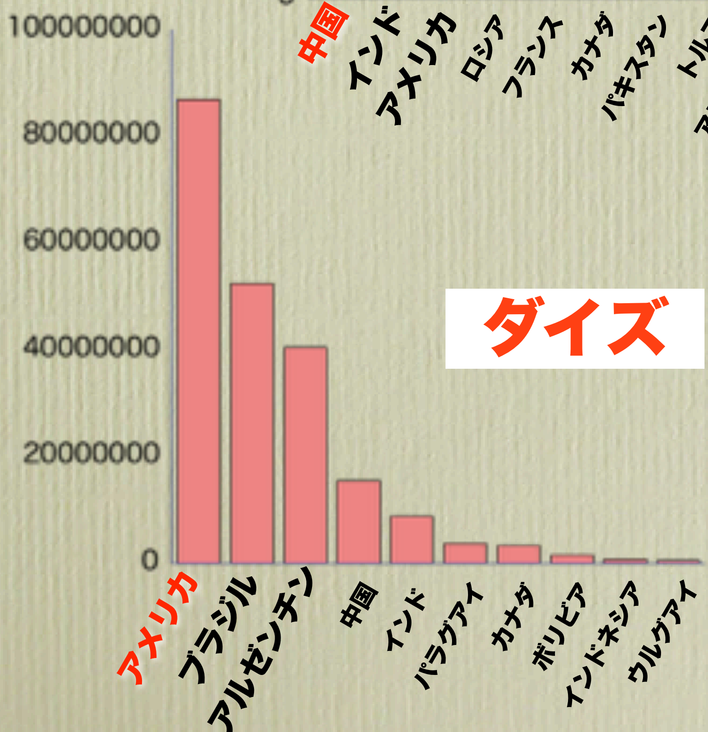
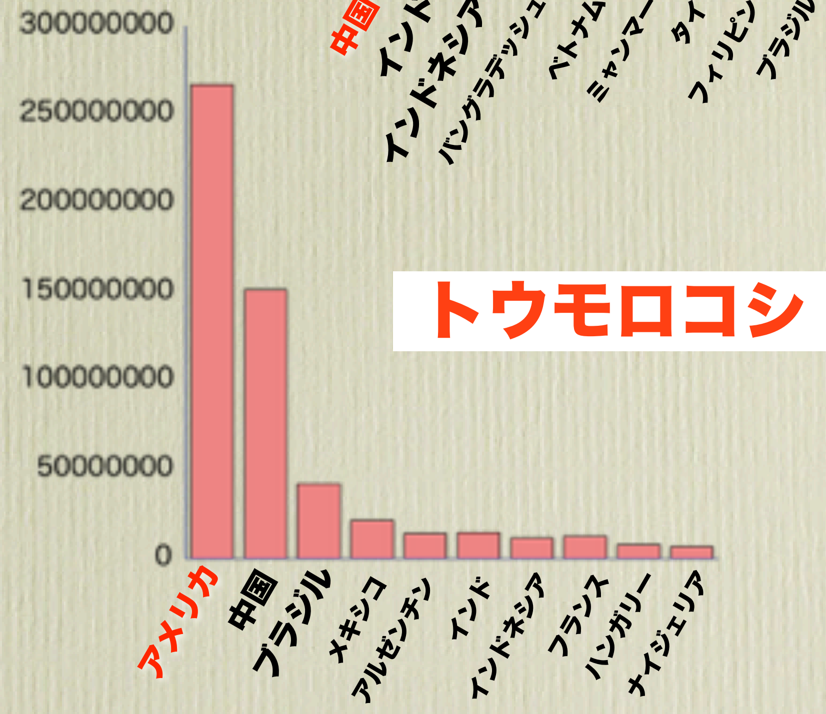
主要穀物の国別生産量

単位：トン
データ：FAOSTAT
2006年実績



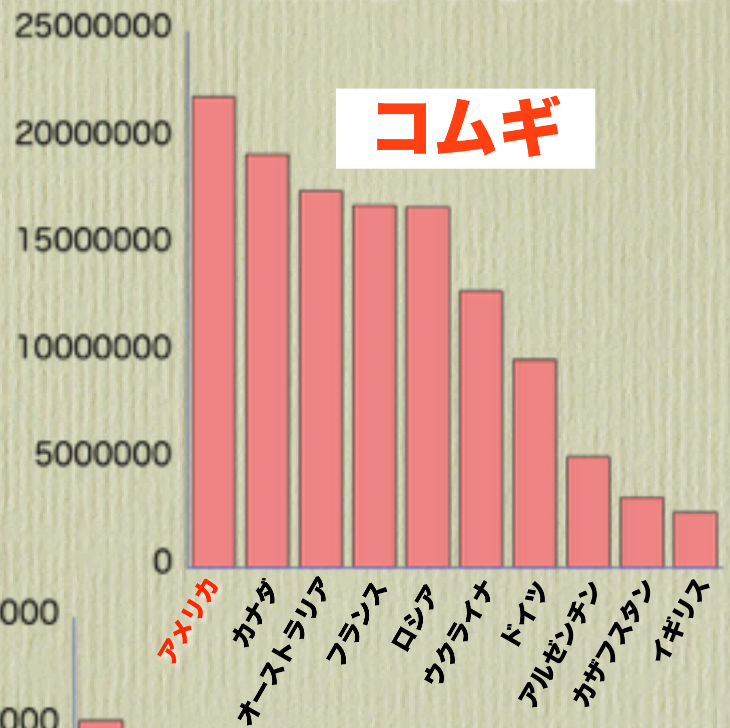


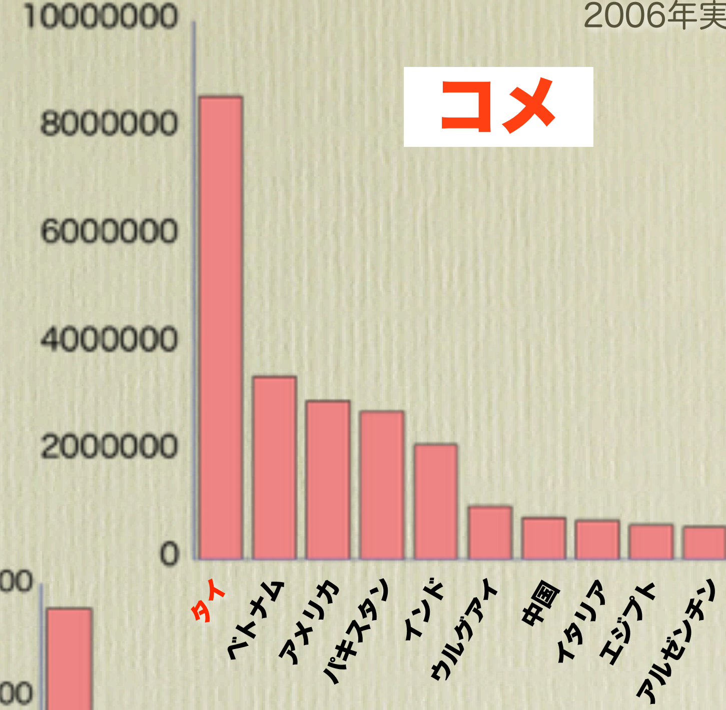


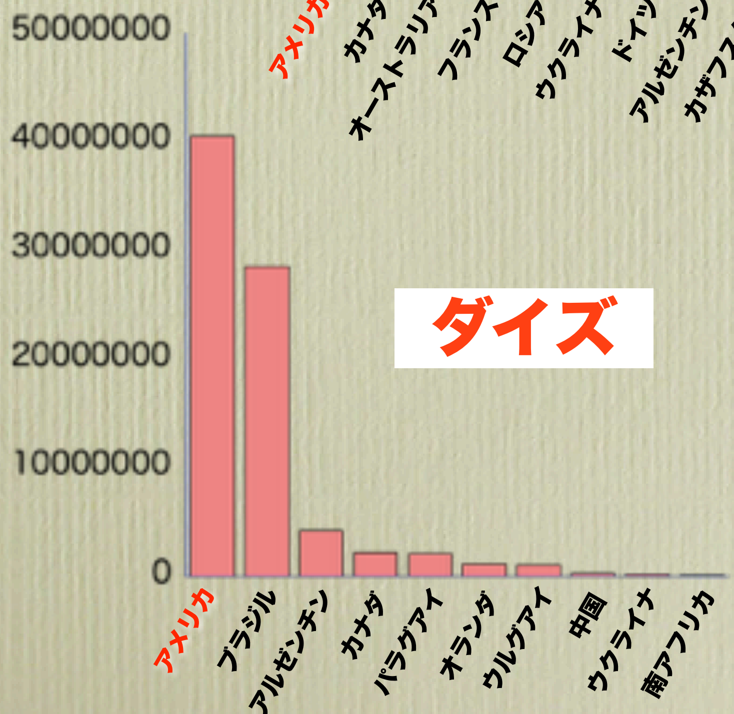


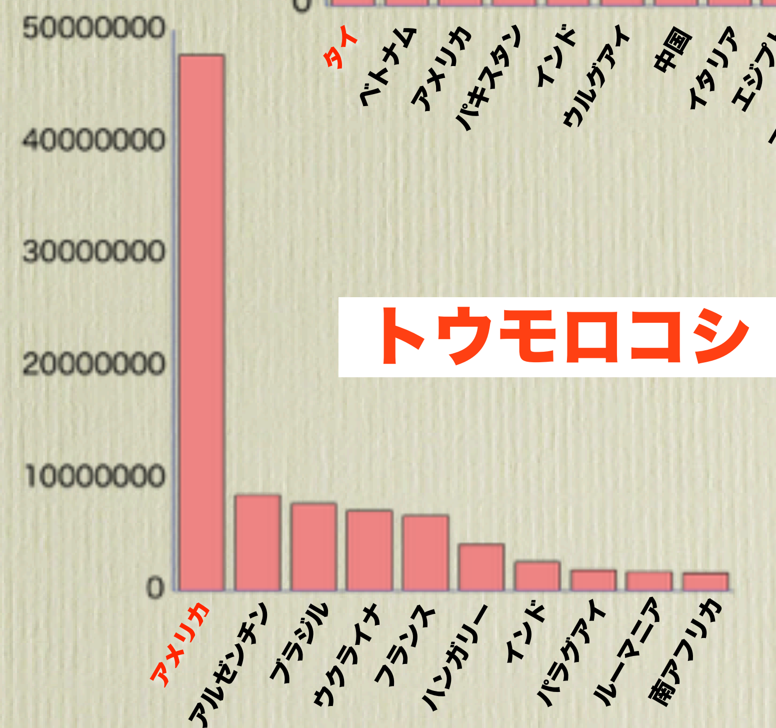
主要穀物の国別輸出量

単位：トン
データ：FAOSTAT
2006年実績

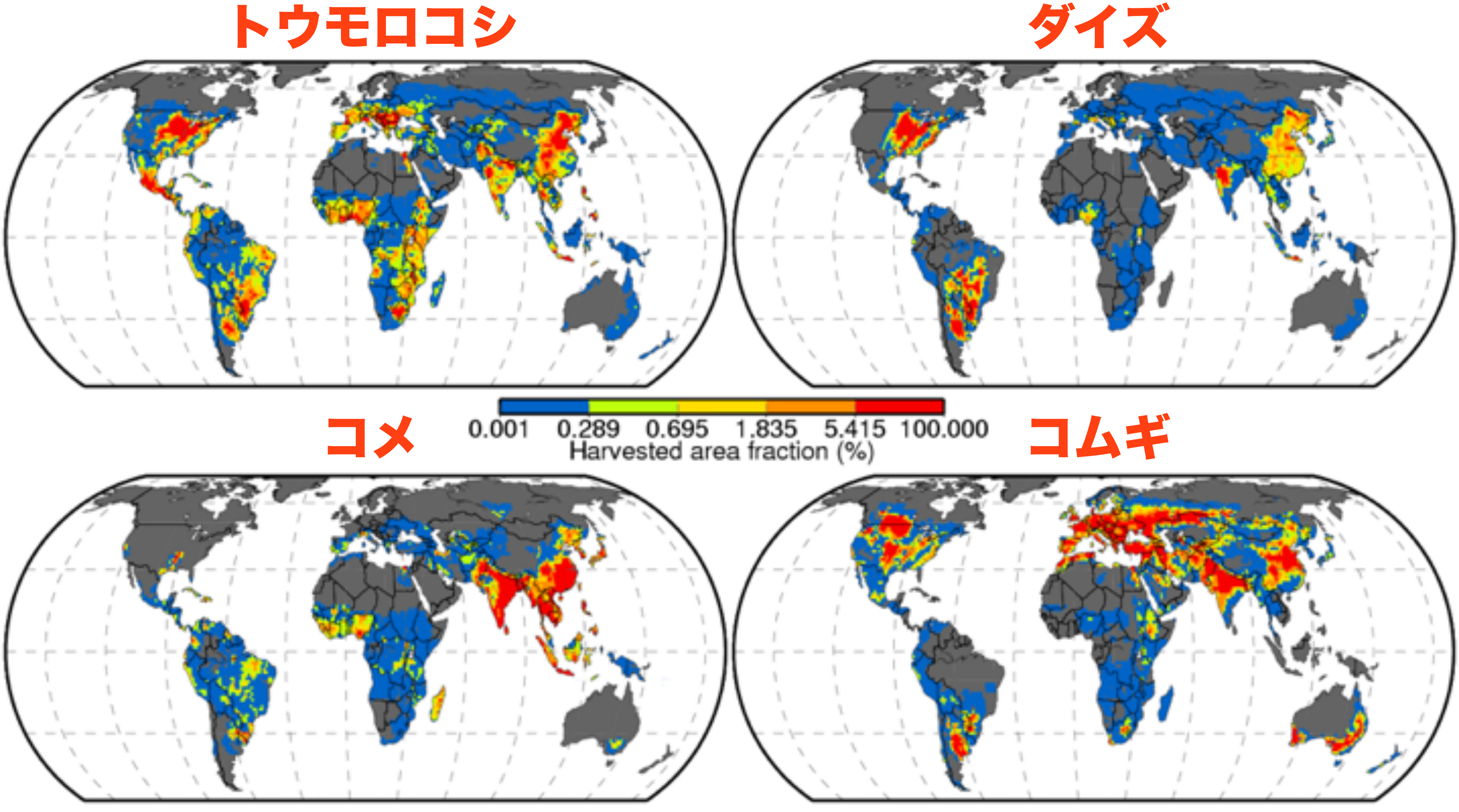




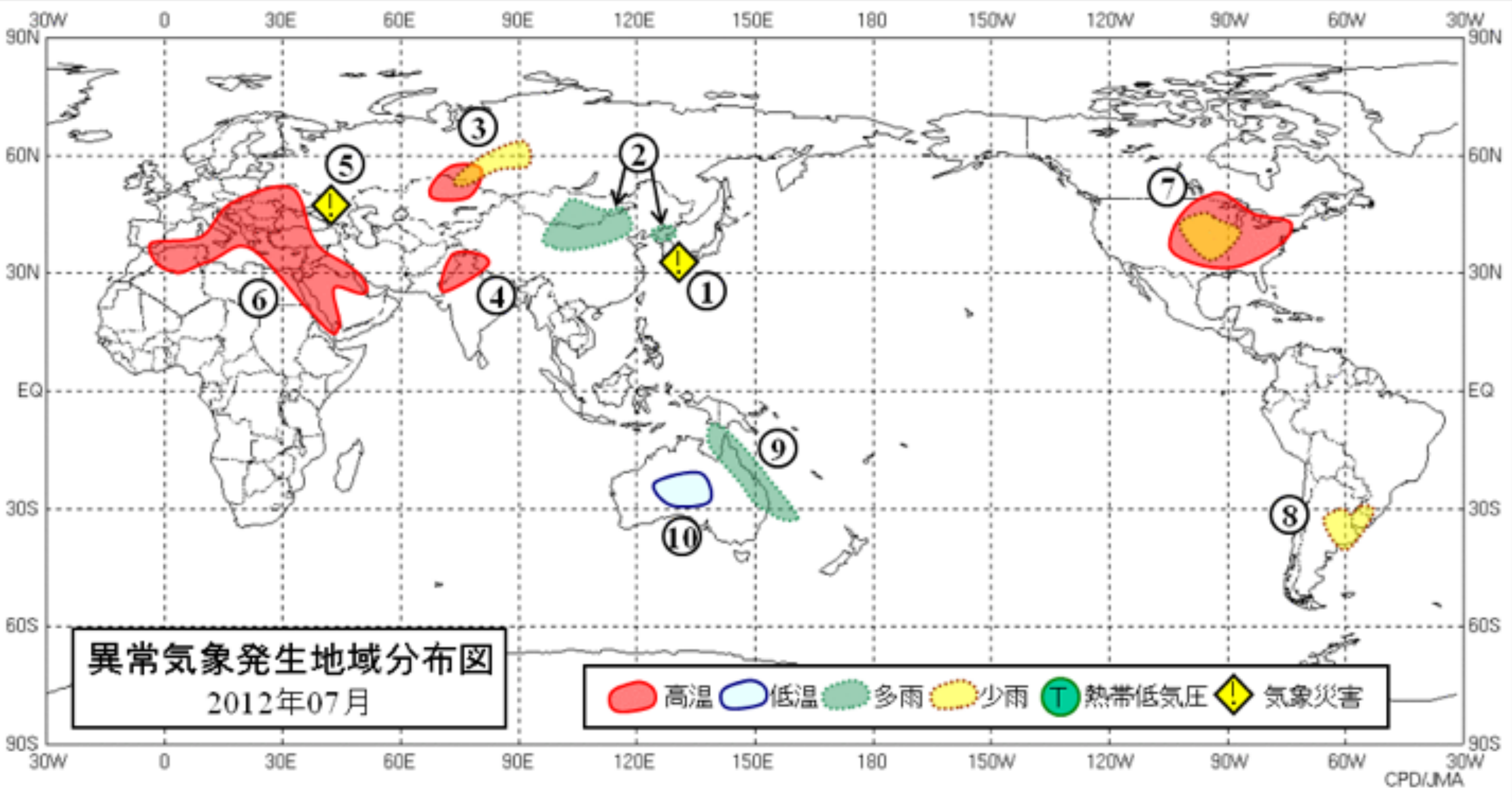




主要穀物の生産地域分布



最近の世界の異常気象

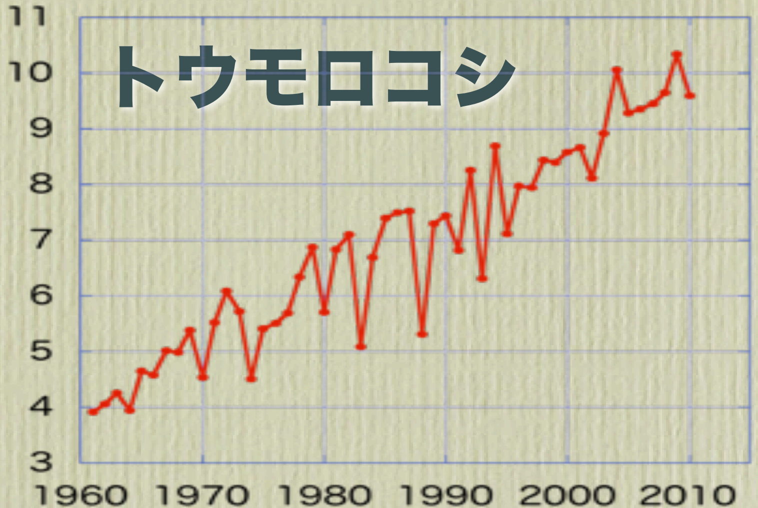


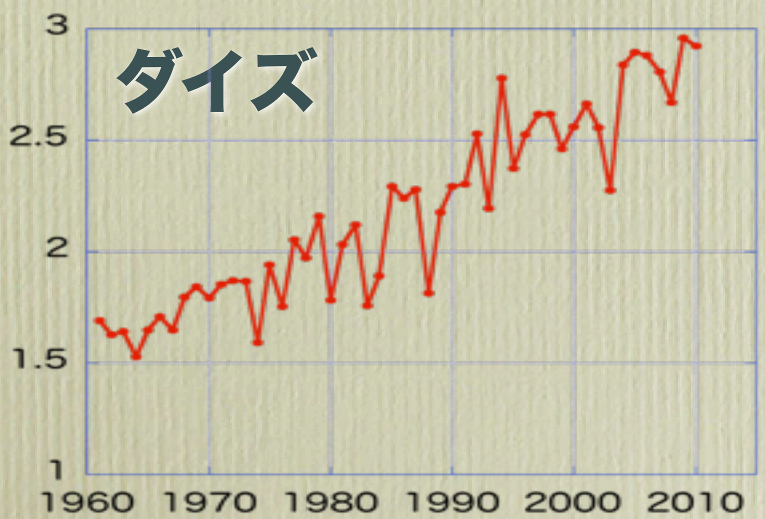
気象庁HP（http://www.data.jma.go.jp/gmd/cpd/monitor/monthly/）

アメリカの収量変動

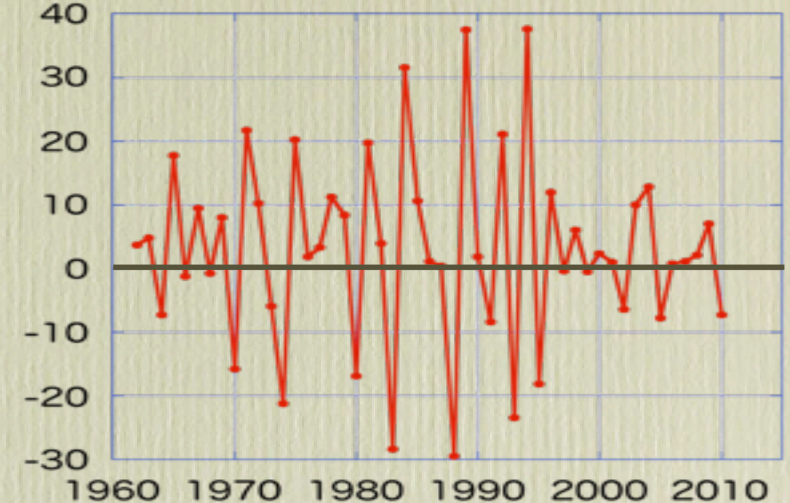
FAOSTAT

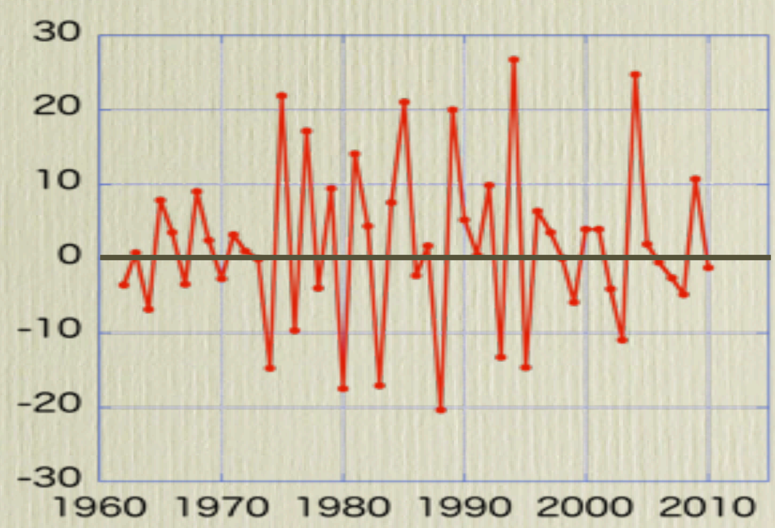
平均収量 (t/ha)





前年比の変動 (%)



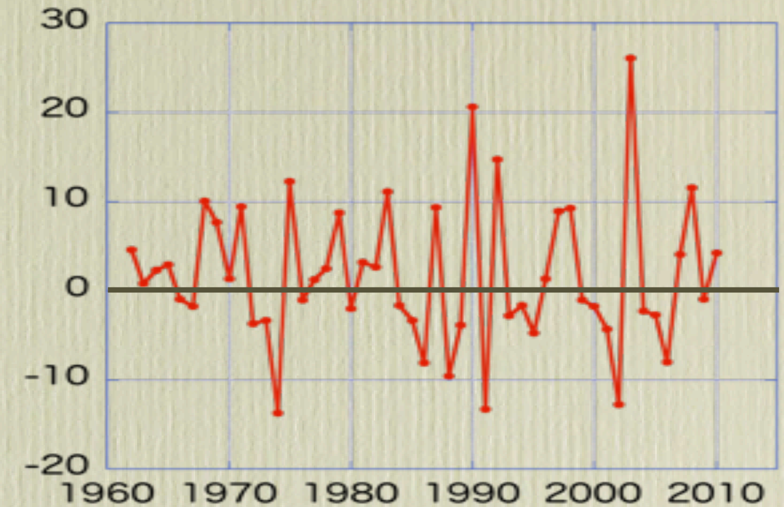


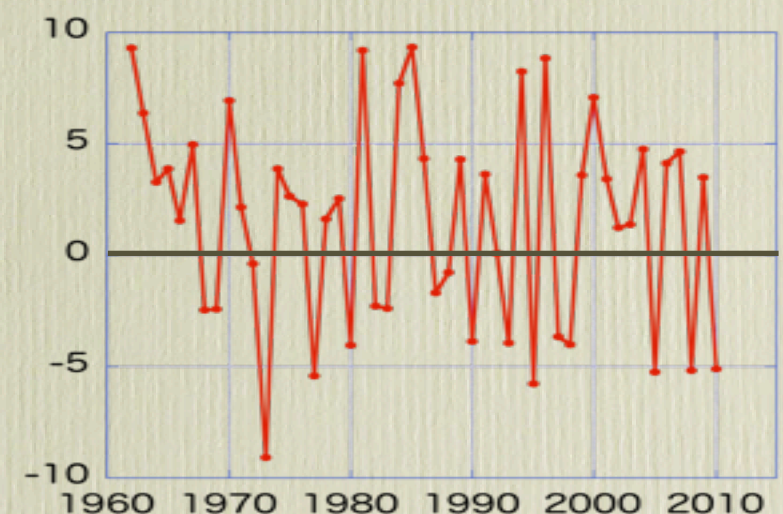
アメリカの収量変動

FAOSTAT

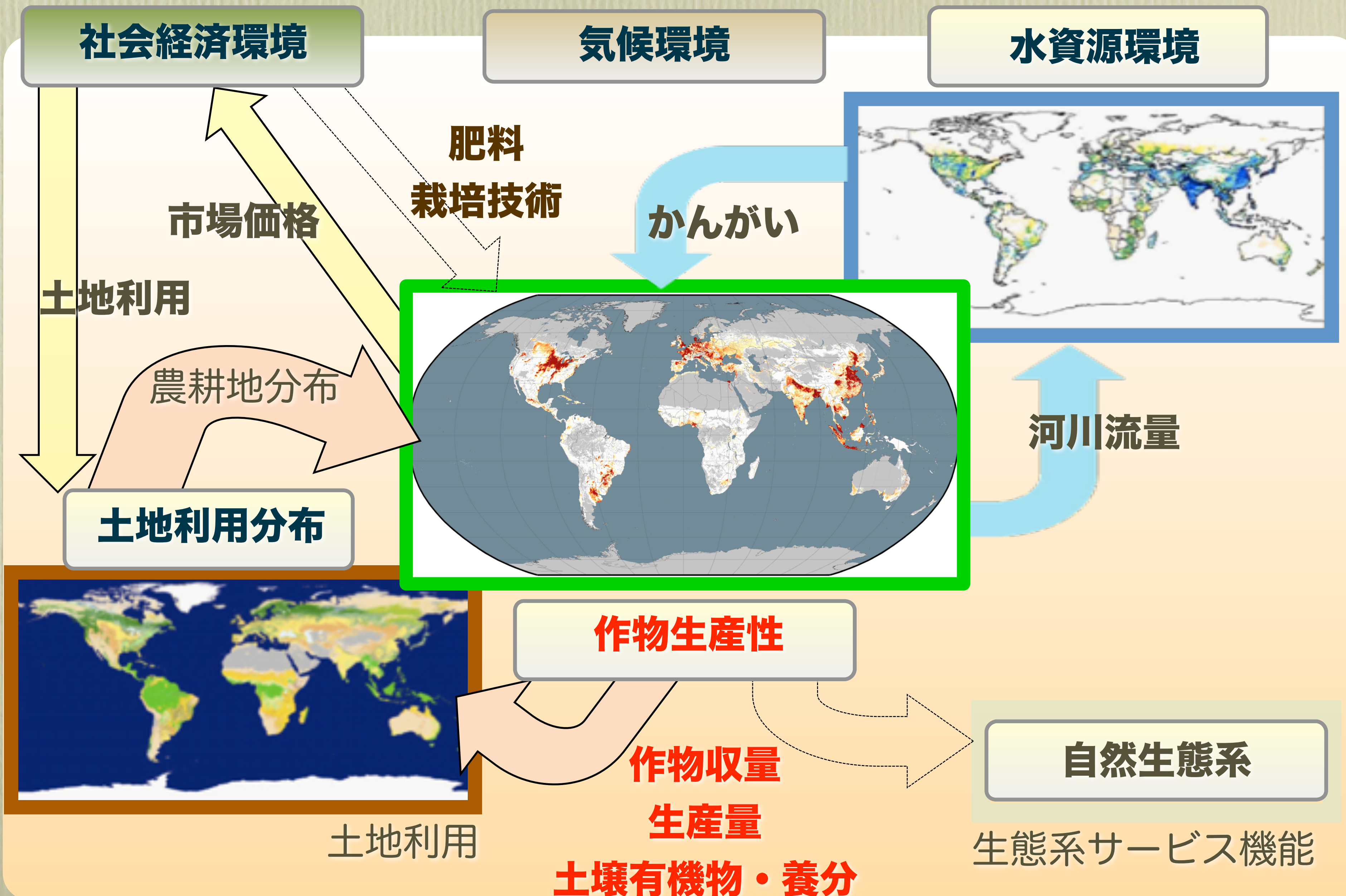
平均収量 (t/ha)

前年比の変動 (%)



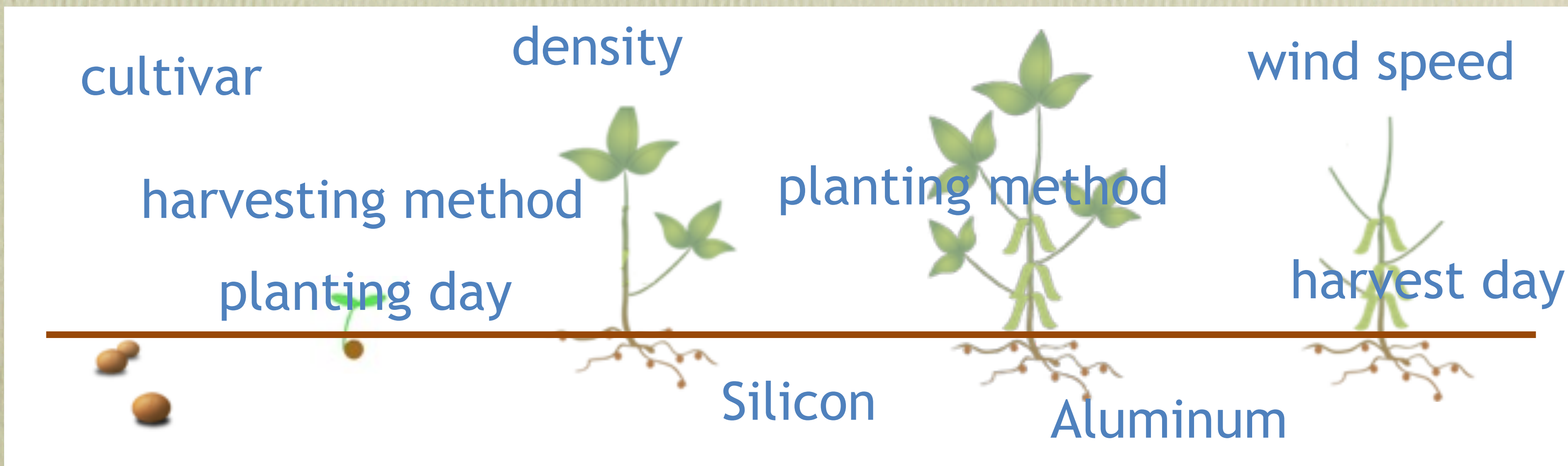


世界の食料生産システム



作物の収量の正確な推定には非常に多くの情報が必要

temperature humidity radiation precipitation



Phosphorus Irrigation cultivation

Nitrogen

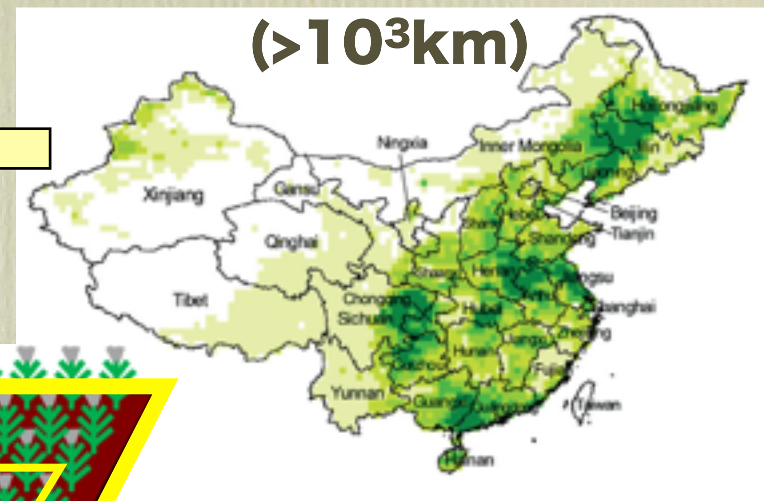
soil improvement pesticide soil texuture

アップスケーリングによる広域作物モデルの作成

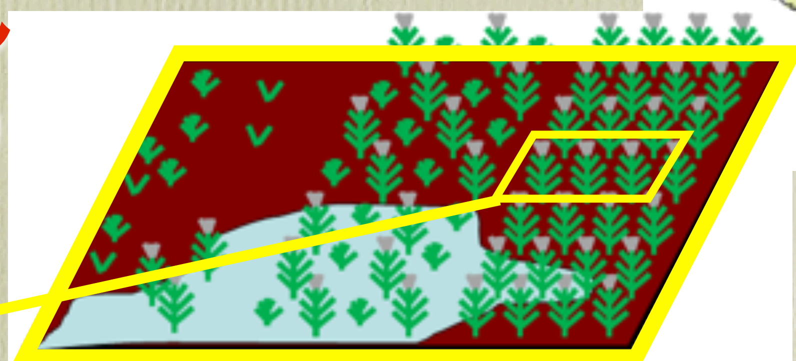
トップダウン的アプローチ　**帰納的**

過去の農業統計情報と環境条件のデータから広域の環境応答を推定

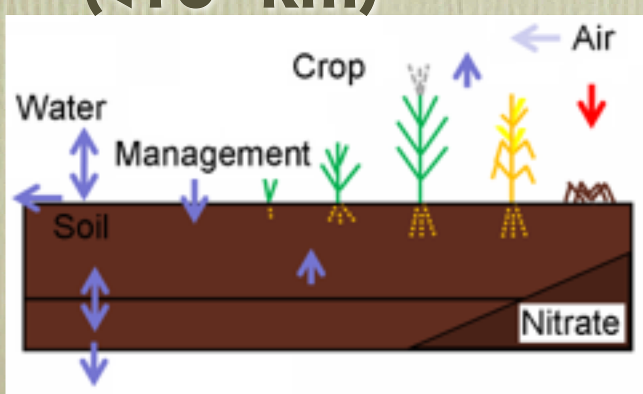
国スケール
($>10^3$km)



対象スケール
($\sim 10^2$km)



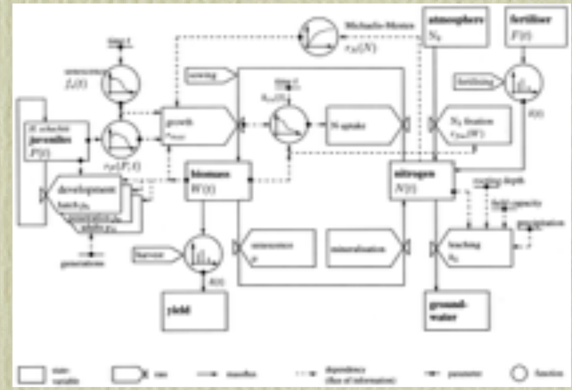
圃場スケール
($<10^{-2}$km)



演繹的
ボトムアップ的アプローチ

圃場スケールの生理・生態的素過程とその不確実性を広域モデルにくり込む

プロセスベースモデル ＋ データ同化



大規模データ

プロセスベースモデルのパラメータ事後分布を作物収量統計データなどのデータを用いてベイズ推定する

多様性はパラメータ推定値に吸収させてしまう

全球について気候の変動・変化の影響を評価できるプロセスベースモデルを作成する

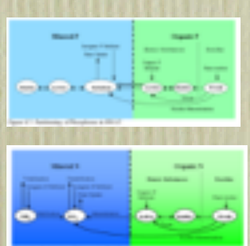
数百万回のMCMC計算に耐えられるように、高速に計算できる作物モデルを再設計・開発

PRYSBI2

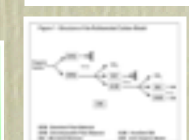
wheat
soybean
maize
rice

1. 光合成過程は反応速度論的なモデル (Farquhar model)

2. 光合成産物の分配ルールなど、できる限り簡略化

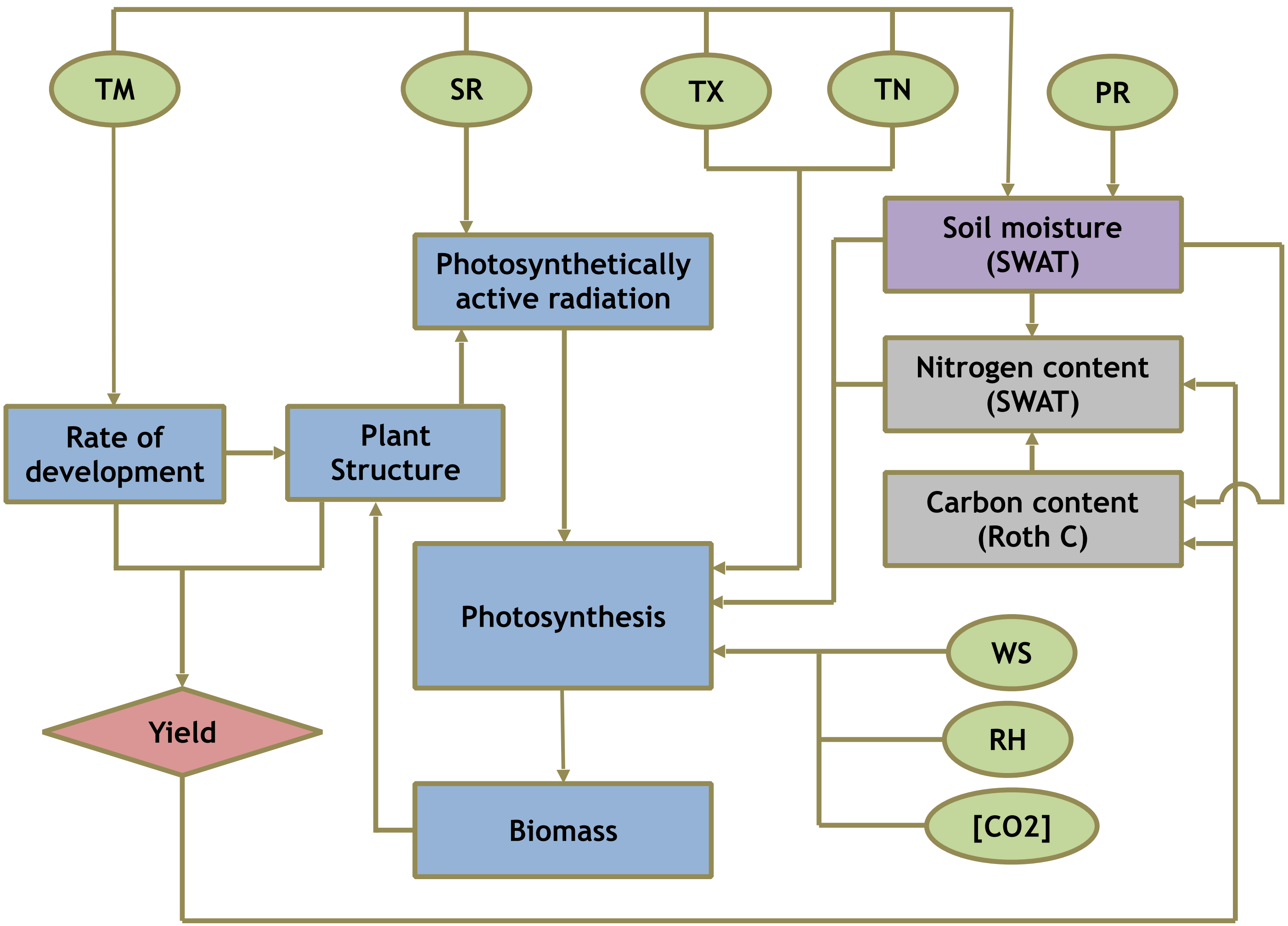


SWAT Soil & Water Assessment Tool



RothC

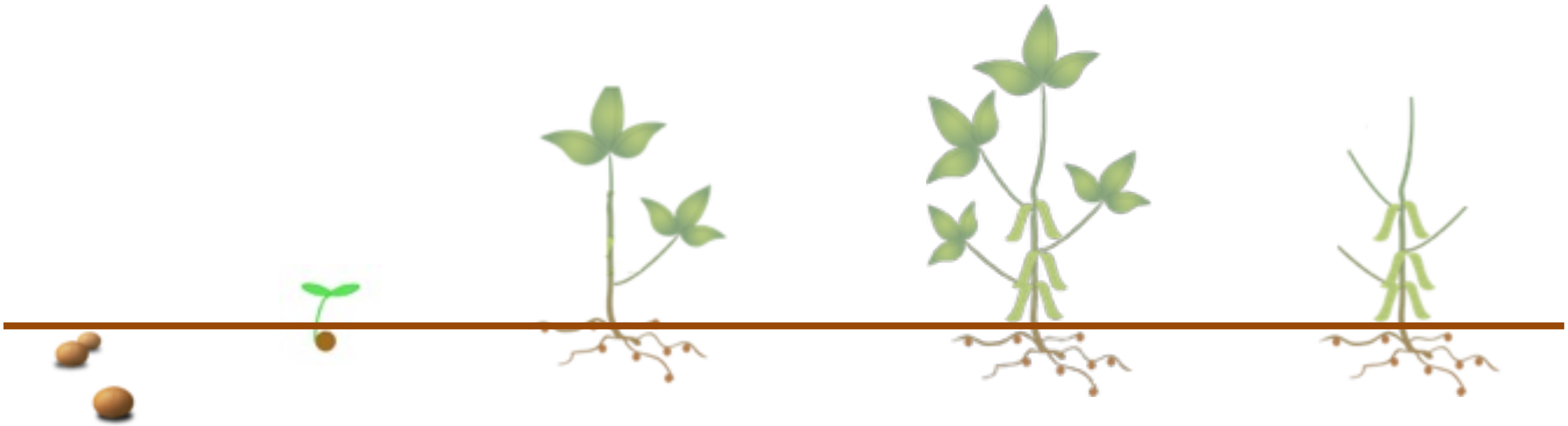
Model structure of PRYSBI-2



生育は積算温度で決まると仮定

$$HU_{td} = \min(0, TM_{td} - tm_{\mathrm{base}})$$

$$THU_{td} = \sum_{i=DOY_{\mathrm{emerge}}}^{td} HU_i$$



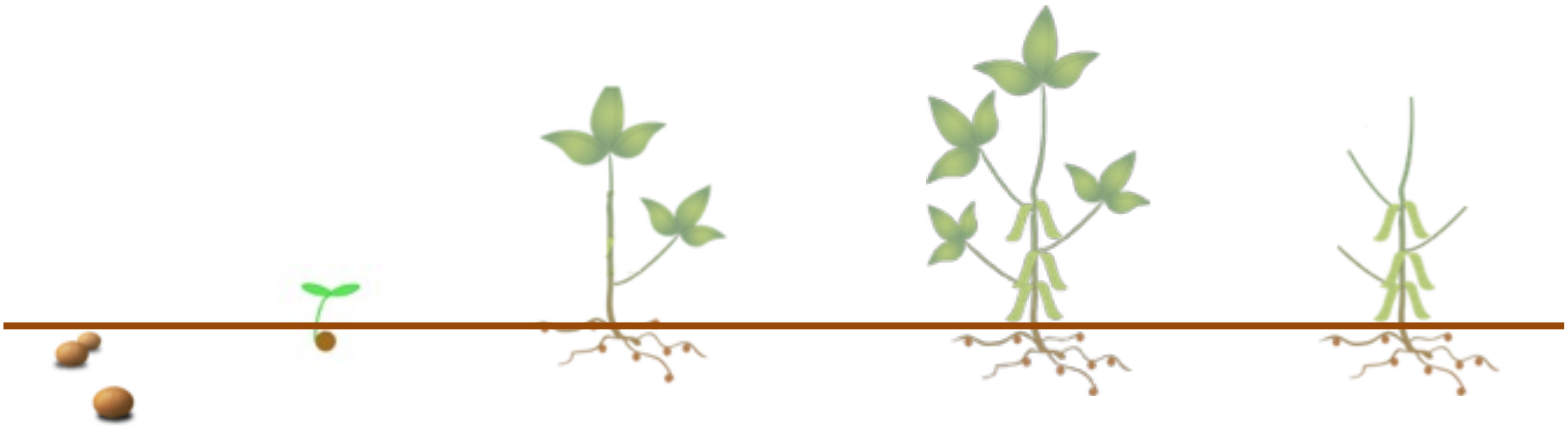
光合成過程は反応速度論的なモデル

Farquhar model

$$V_c - 0.5V_o = \frac{J_{t,td}(C_i - \Gamma)}{4C_i - 8\Gamma}, \quad V_c - 0.5V_o = \frac{V_{cmax(t,td)}(C_i - \Gamma)}{C_i + K_c\left(1 + \frac{[O_2]}{K_o}\right)}$$

Ball model

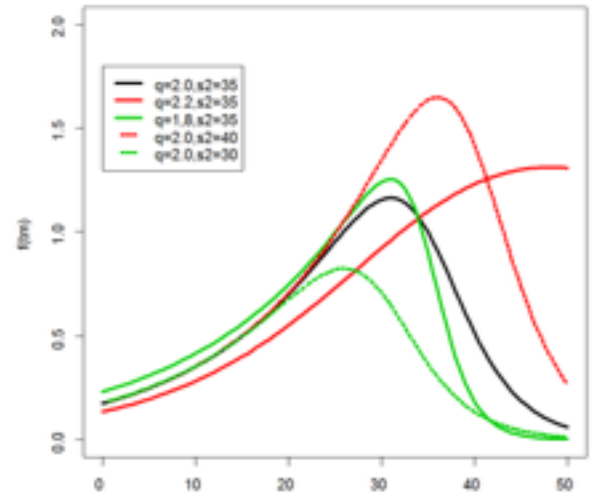
$$G_s = \frac{m \times As \times RH}{C_s} + b'$$



最大カルボキシル反応と呼吸速度の温度依存性

$$C_{\mathrm{vcmax}(t,td)} = q^{\left(\frac{TM_{t,td}-25}{10}\right)} \Big/ \left\{1+\exp\left[s_1\left(TM_{t,td}-s_2\right)\right]\right\}$$

$$C_{\mathrm{dark}(t,td)} = q^{\left(\frac{TM_{t,td}-25}{10}\right)} \Big/ \left\{1+\exp\left[s_3\left(TM_{t,td}-s_4\right)\right]\right\}$$

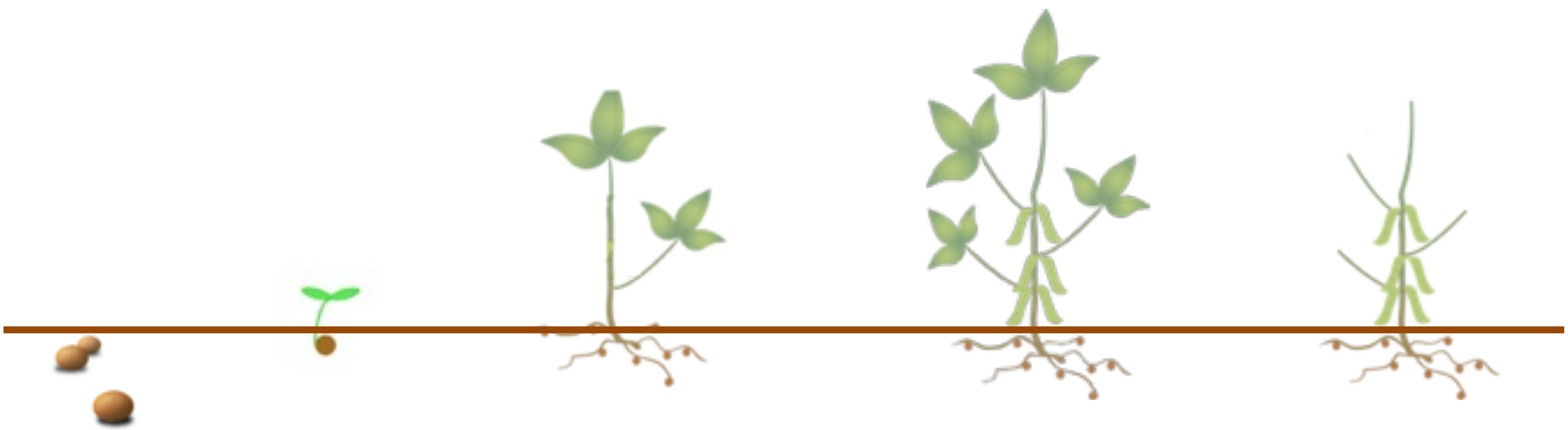


水分ストレスはパラメータで補正

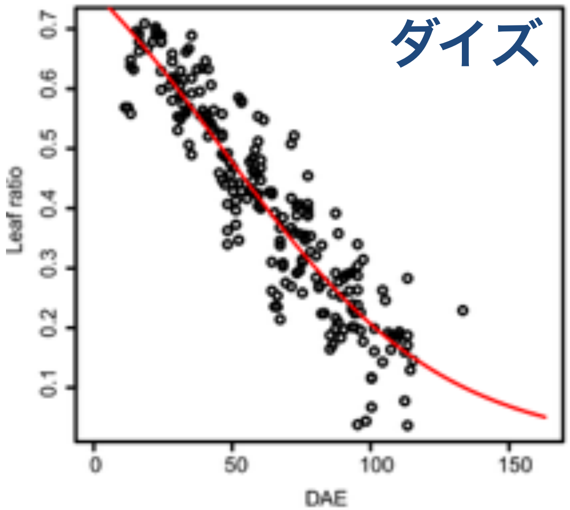
SWAT | Soil & Water Assessment Tool

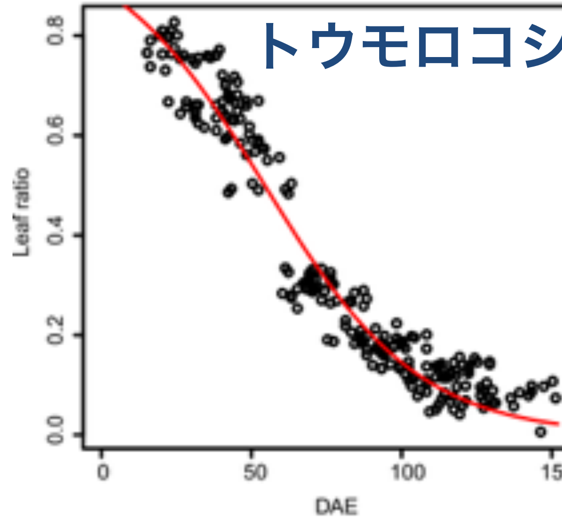
$$W_{\mathrm{stress}(td)} = \max\left(w_{\mathrm{coef}} \times WSTRS,\ 1.0\right)$$

$$V_{\mathrm{cmax}(t,td)} = C_{\mathrm{vcmax}(t,td)} \times W_{\mathrm{stress}(td)} \times v_{\mathrm{cmax}}$$

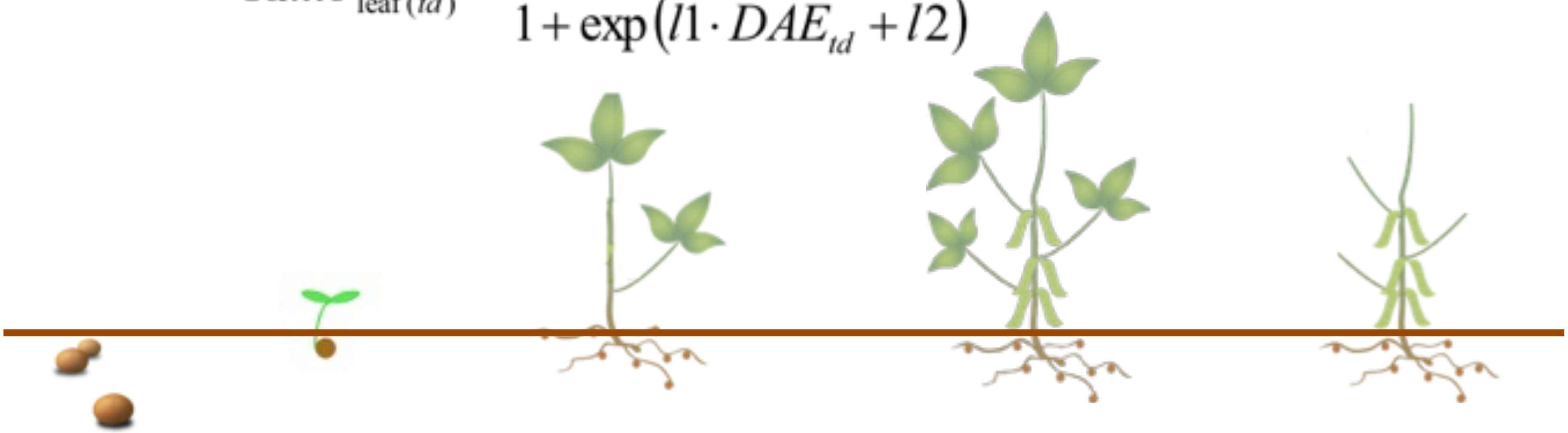


光合成産物の分配ルールの簡略化





$$Ratio_{\mathrm{leaf}(td)} = \frac{1}{1 + \exp\left(l1 \cdot DAE_{td} + l2\right)}$$



Global Ecology and Biogeography, (Global Ecol. Biogeogr.) (2013)

A Journal of Macroecology

d Biogeography

RESEARCH PAPER

Historical changes in global yields: major cereal and legume crops from 1982 to 2006

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[1]Agro-Meteorology Division, National Institute for Agro-Environmental Sciences, 3-1-3 Kannondai, Tsukuba, Ibaraki 305-8604, Japan, [2]Instituto de Clima y Agua, Instituto Nacional de Tecnologia Agropecuaria, Hurlingham, Argentina, [3]Department of the Geographical Network of Field Experiments, All-Russia Institute for Agrochemistry, Moscow, Russia, [4]Department of Earth and Planetary Science, Graduate School of Science, The University of Tokyo, Tokyo, Japan, [5]Institute for Soil, Climate and Water, Agricultural Research Council, Pretoria, South Africa, [6]Development Research Division, Japan International Research Center for Agricultural Science, Tsukuba, Japan

ABSTRACT

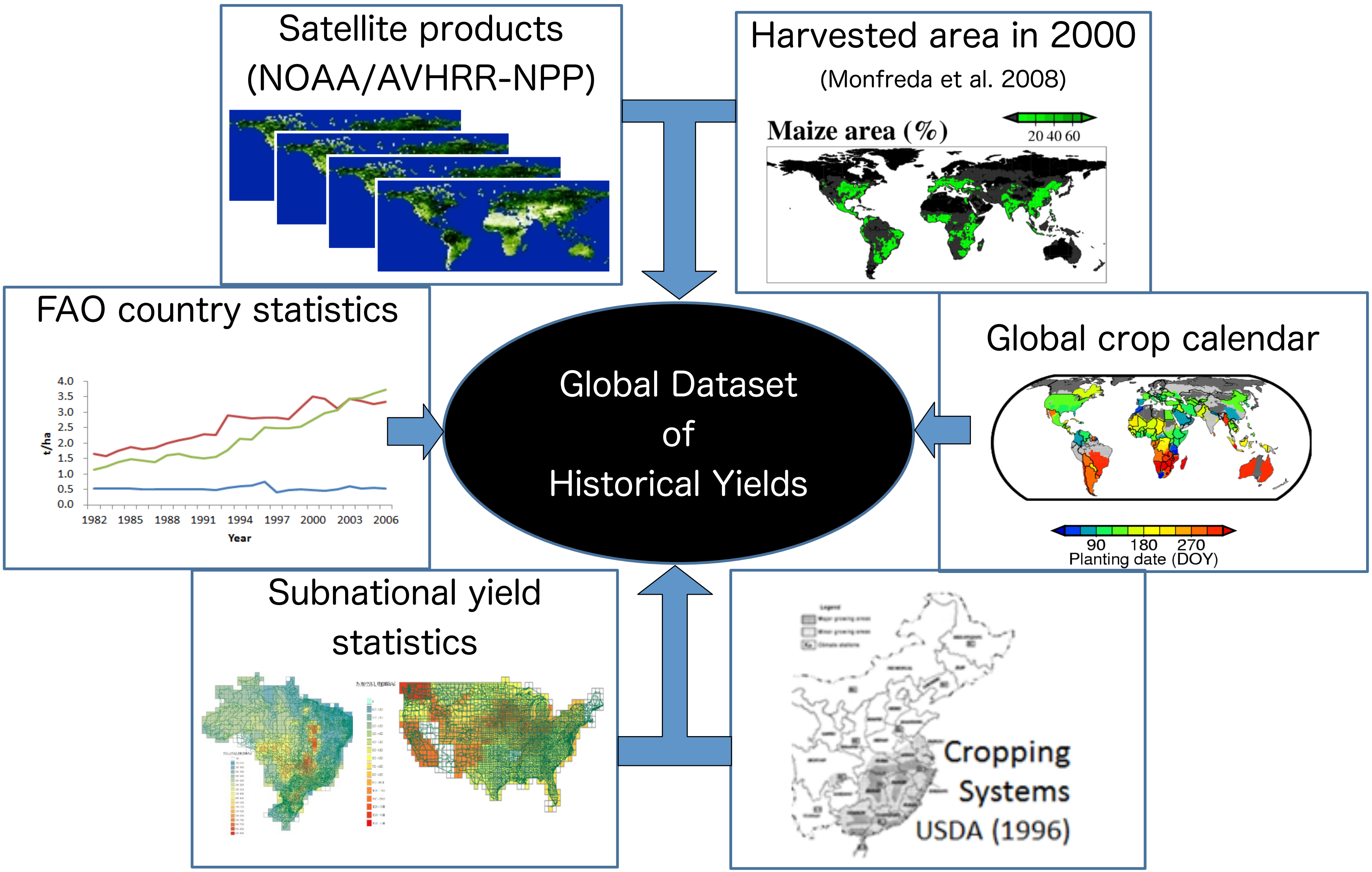
Aim Recent changes in crop yields have implications for future global food security, which are likely to be affected by climate change. We developed a spatially explicit global dataset of historical yields for maize, soybean, rice and wheat to explore the historical changes in mean, year-to-year variation and annual rate of change in yields for the period 1982–2006.

Location This study was conducted at the global scale.

Methods We modelled historical and spatial patterns of yields at a grid size of 1.125° by combining global agricultural datasets related to the crop calendar and harvested area in 2000, country yield statistics and satellite-derived net primary production. Modelled yields were compared with other global datasets of yields in 2000 (M3-Crops and MapSPAM) and subnational yield statistics for 23 major crop-producing countries. Historical changes in modelled yields were then examined.

Results Modelled yields explained 45–81% of the spatial variation of yields in 2000 from M3-Crops and MapSPAM, with root-mean-square errors of 0.5–1.8 t ha^{-1}. Most correlation coefficients between modelled yield time series and subnational yield statistics for the period 1982–2006 in major crop-producing regions were greater than 0.8. Our analysis corroborated the incidence of reported yield stagnations and collapses and showed that low and mid latitudes in the Southern Hemisphere (0–40°S) experienced significantly increased year-to-year variation in maize, rice and wheat yields in 1994–2006 compared with that in 1982–93.

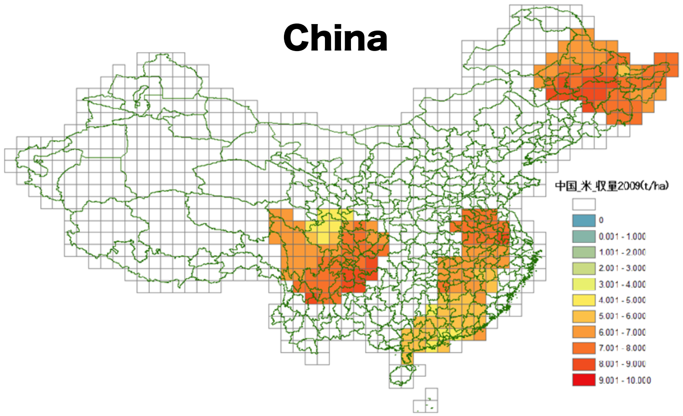
グリッド収量データ

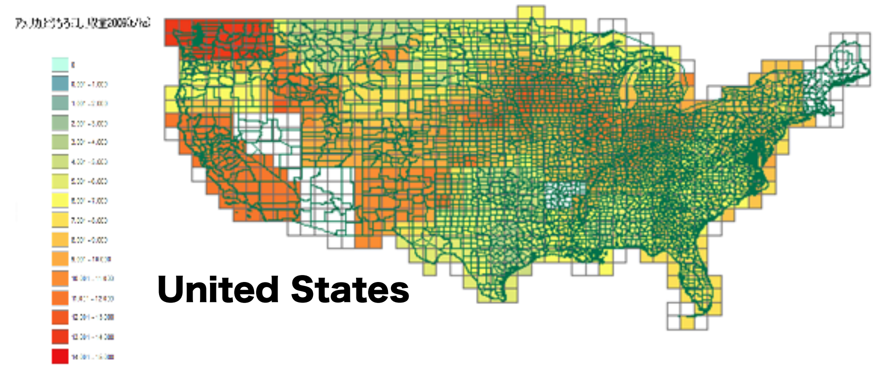

Satellite products
(NOAA/AVHRR-NPP)
Harvested area in 2000
(Monfreda et al. 2008)
Maize area (%)
20 40 60
FAO country statistics
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
t/ha
1982 1985 1988 1991 1994 1997 2000 2003 2006
Year
Global Dataset
of
Historical Yields
Global crop calendar
90 180 270
Planting date (DOY)
Subnational yield
statistics
Cropping
Systems
USDA (1996)

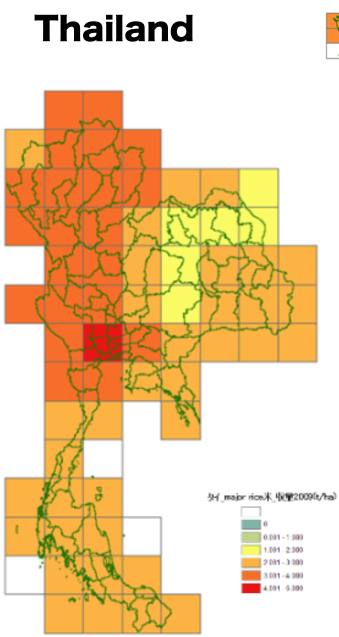
グリッド収量データ

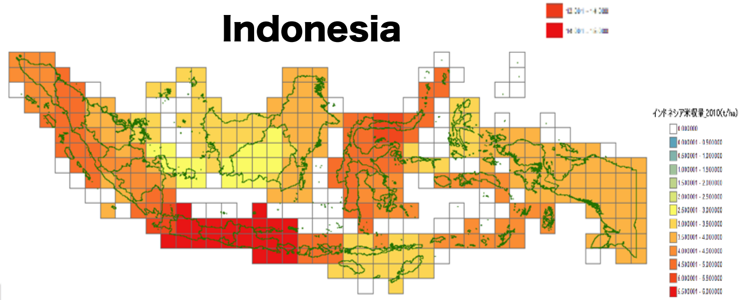
収量時空間分布データ（1982-2006, 1.125 lon/lat）

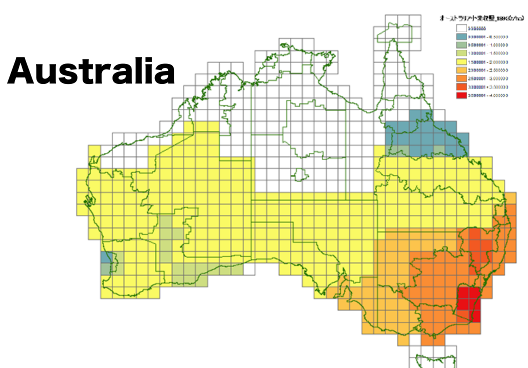
行政単位の農業統計資料を収集
グリッド化した

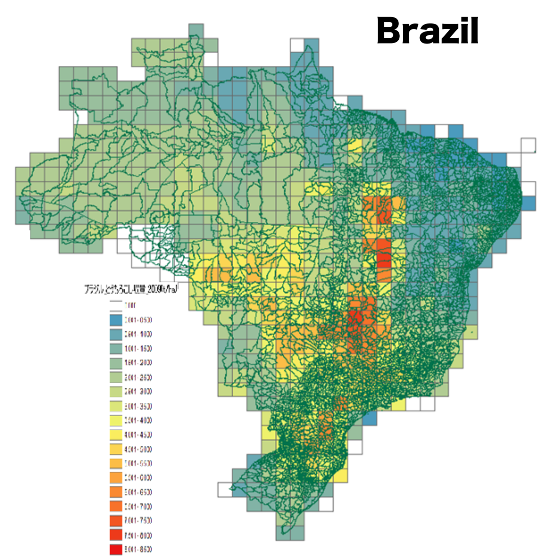


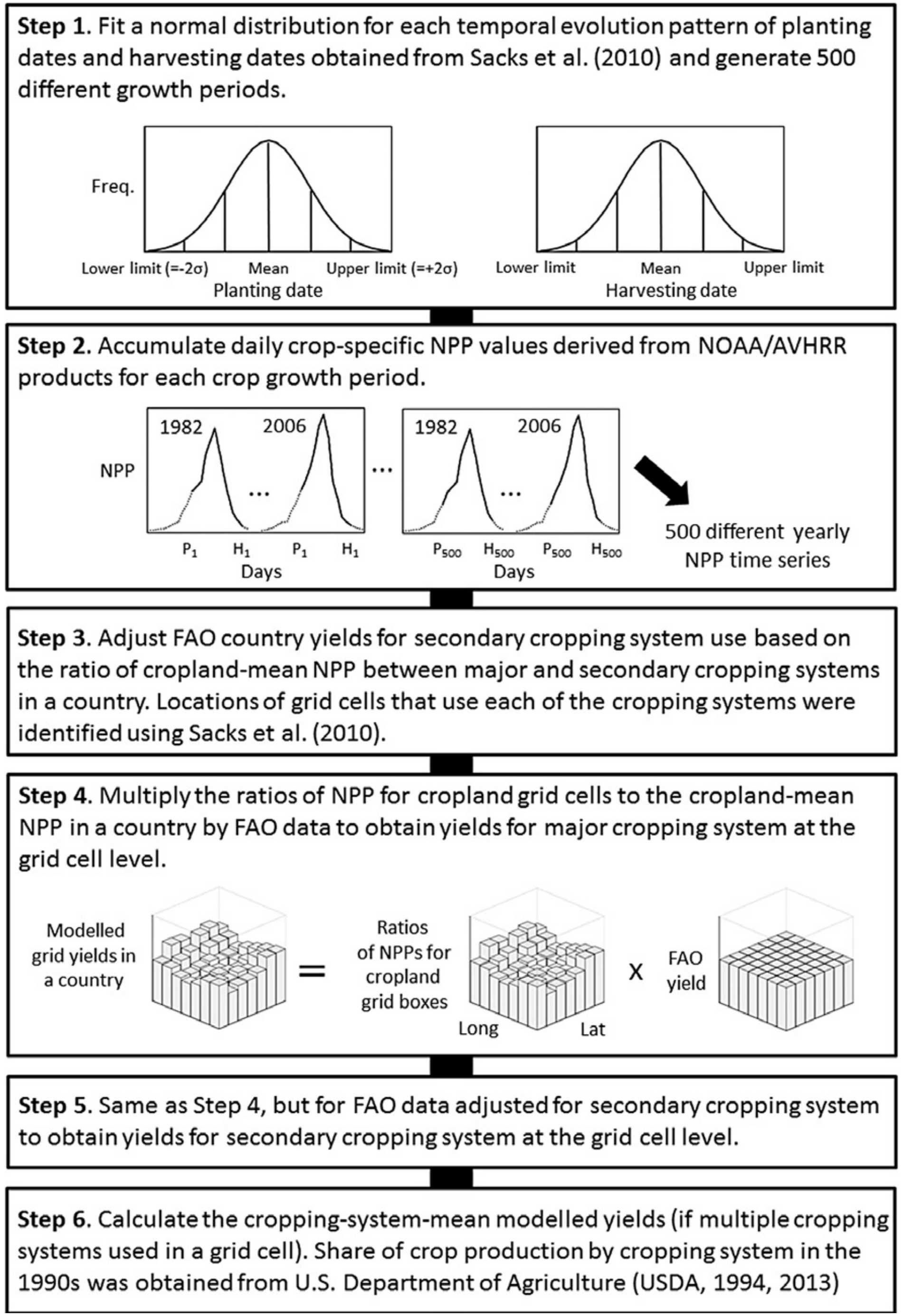











Step 1. Fit a normal distribution for each temporal evolution pattern of planting dates and harvesting dates obtained from Sacks et al. (2010) and generate 500 different growth periods.
Freq.
Lower limit (=-2σ)
Mean
Upper limit (=+2σ)
Planting date
Lower limit
Mean
Upper limit
Harvesting date
Step 2. Accumulate daily crop-specific NPP values derived from NOAA/AVHRR products for each crop growth period.
NPP
1982
2006
1982
2006
…
P_1 H_1 P_1 H_1
Days
P_{500} H_{500} P_{500} H_{500}
Days
500 different yearly NPP time series
Step 3. Adjust FAO country yields for secondary cropping system use based on the ratio of cropland-mean NPP between major and secondary cropping systems in a country. Locations of grid cells that use each of the cropping systems were identified using Sacks et al. (2010).
Step 4. Multiply the ratios of NPP for cropland grid cells to the cropland-mean NPP in a country by FAO data to obtain yields for major cropping system at the grid cell level.
Modelled grid yields in a country
=
Ratios of NPPs for cropland grid boxes
Long
Lat
X
FAO yield
Step 5. Same as Step 4, but for FAO data adjusted for secondary cropping system to obtain yields for secondary cropping system at the grid cell level.
Step 6. Calculate the cropping-system-mean modelled yields (if multiple cropping systems used in a grid cell). Share of crop production by cropping system in the 1990s was obtained from U.S. Department of Agriculture (USDA, 1994, 2013)

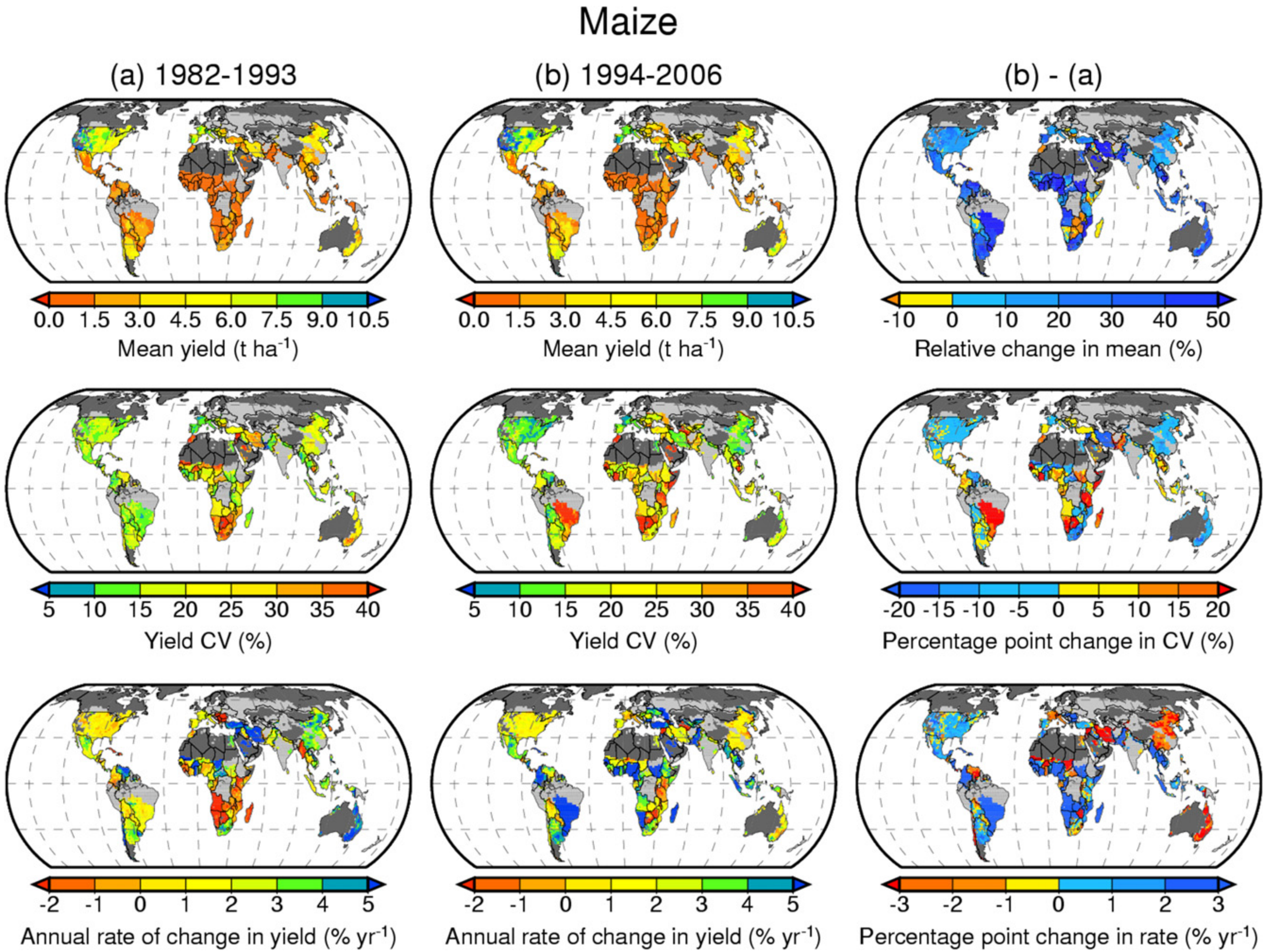
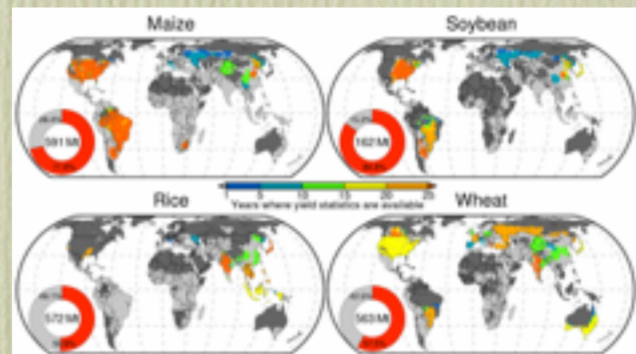


Figure 4 Means (upper row), coefficients of variation (CVs, middle row) and annual rates of change (bottom row) in modelled maize yields in 1982–93 (left column) and 1994–2006 (middle column), and differences in values of the statistics between the two periods (right column). Light gray indicates that no modelled yields were available due to the lack of crop calendar data. Dark gray indicates non-cropland grid cells.

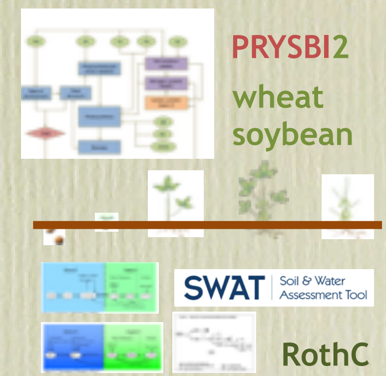
全球収量時系列データを用いたパラメータのベイズ推定

Global yield data base



パラメータ分布の推定

technical coefficient
Trend of technical coefficient
Temperature sensitivity
Total heat unit
Leaf structure



DiffeRential Evolution Adaptive Metropolis (DREAM) (20 chains) を使用

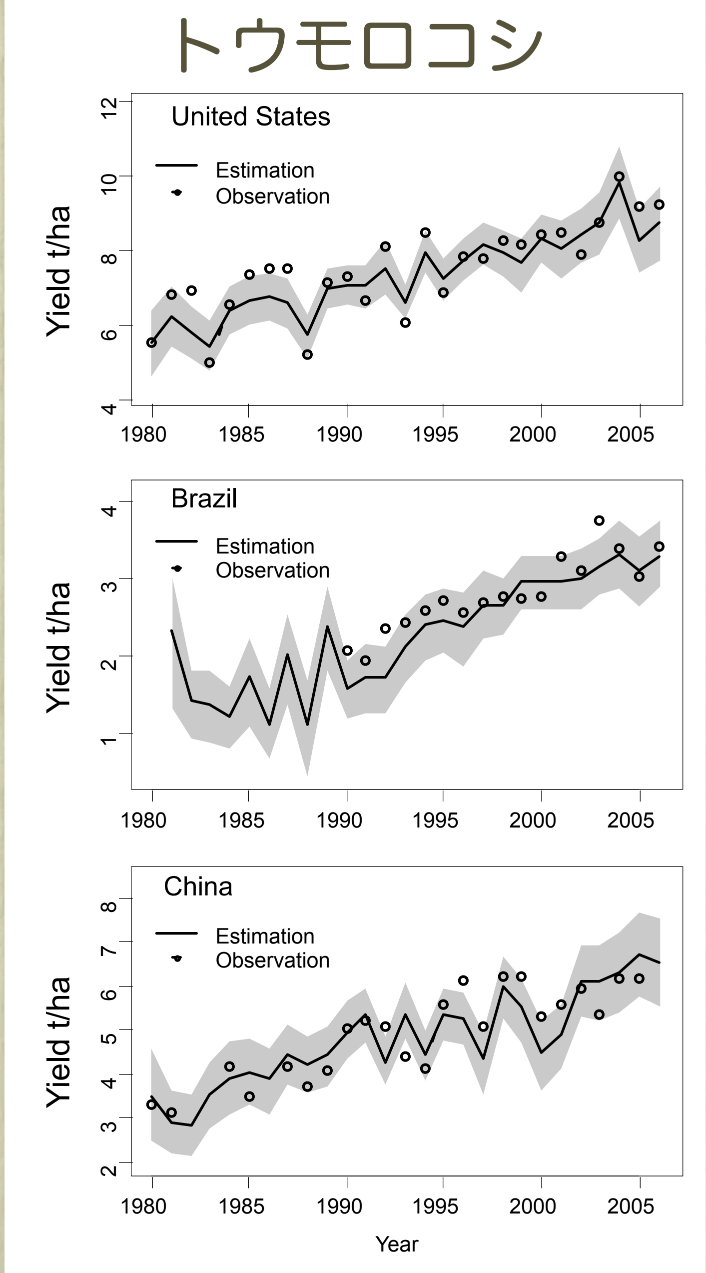
Morgan et al. (2009) *IJNSNS*

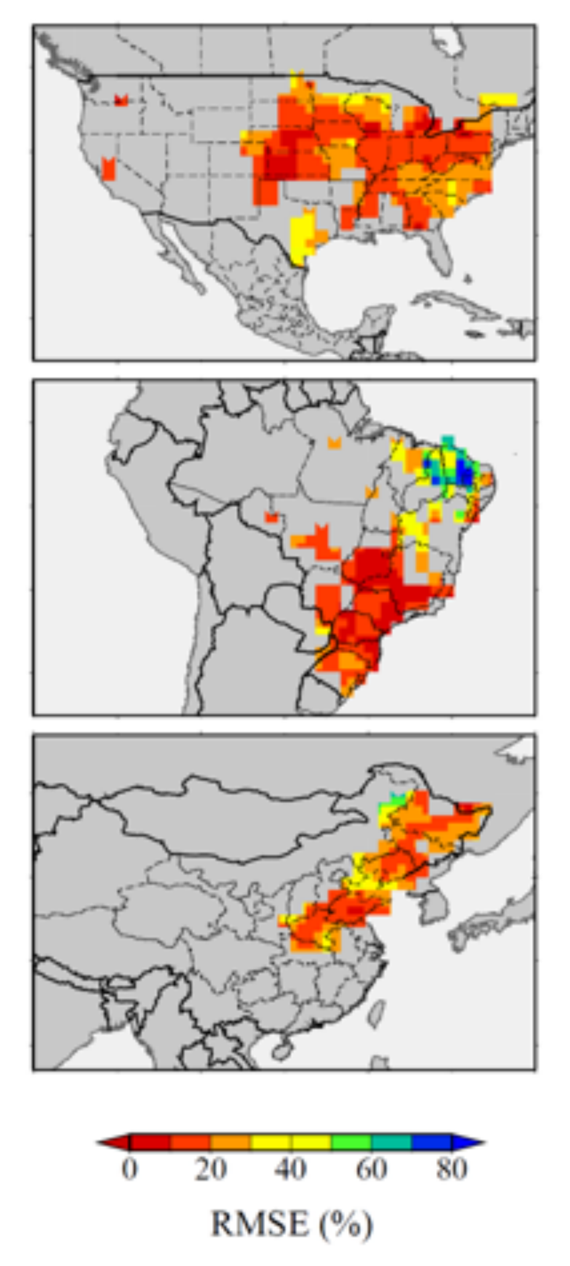
JAMSTEC Cluster System

Error structure

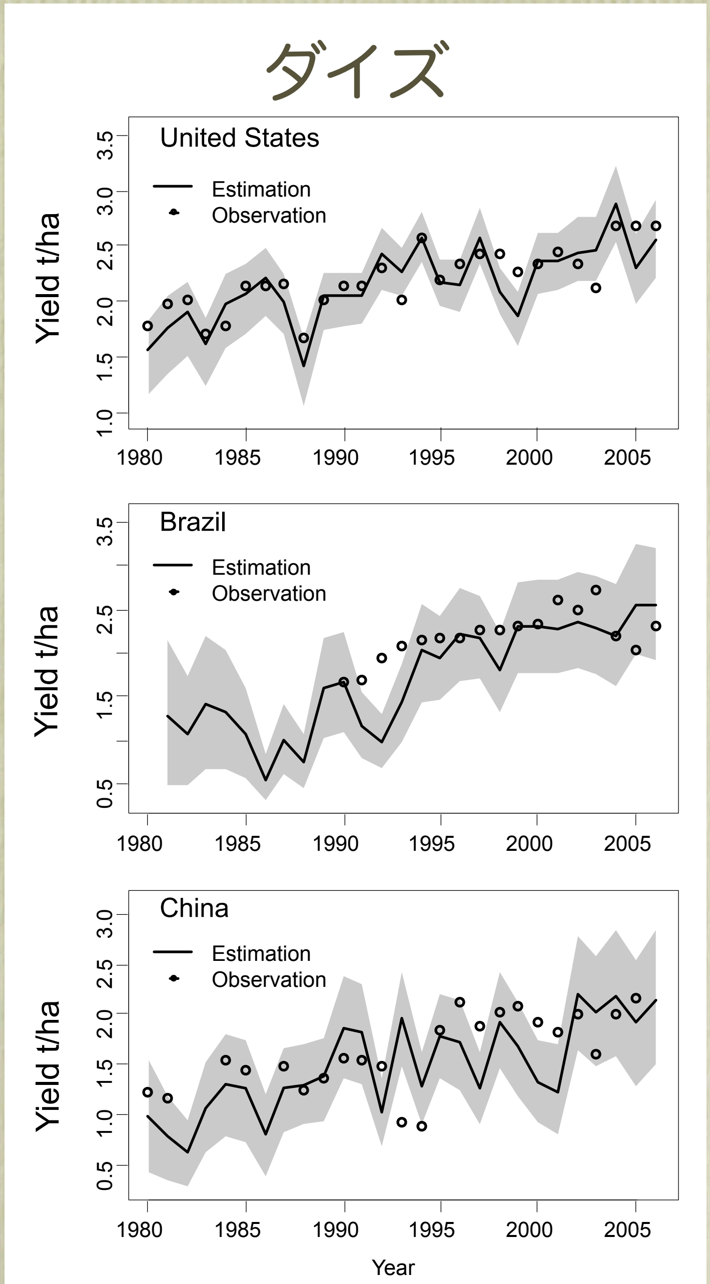
$$Error_{yield\ (time)} \sim N(0, \sigma_{yield})$$

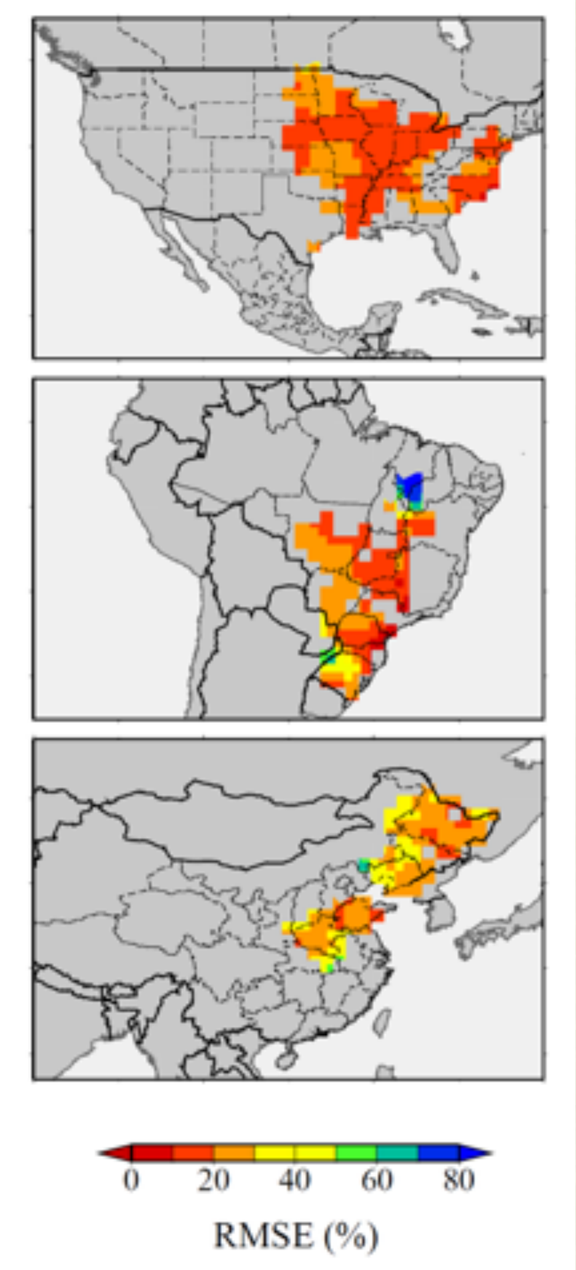
モデルの再現性


トウモロコシ
United States
Estimation
Observation
Brazil
Estimation
Observation
China
Estimation
Observation
Yield t/ha
Year
1980
1985
1990
1995
2000
2005

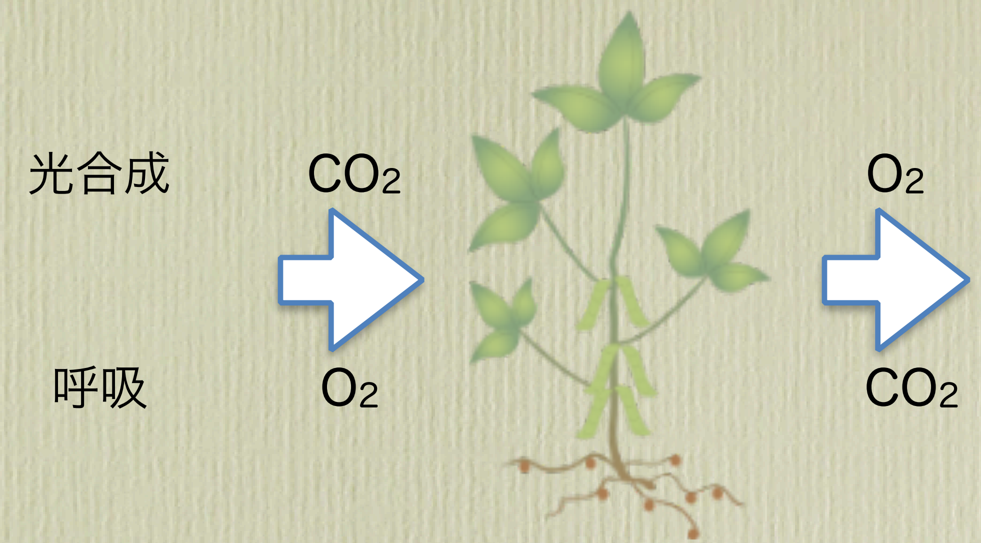

0
20
40
60
80
RMSE (%)

モデルの再現性


ダイズ
United States
Estimation
Observation
Brazil
Estimation
Observation
China
Estimation
Observation
Yield t/ha
Year
1.0
1.5
2.0
2.5
3.0
3.5
0.5
1980
1985
1990
1995
2000
2005


0
20
40
60
80
RMSE (%)

大気CO_2濃度と気温の上昇が及ぼす影響



昼：光合成＞呼吸

夜：光合成＜呼吸

プラスの効果

大気CO_2の濃度の増大によって光合成速度は増加する

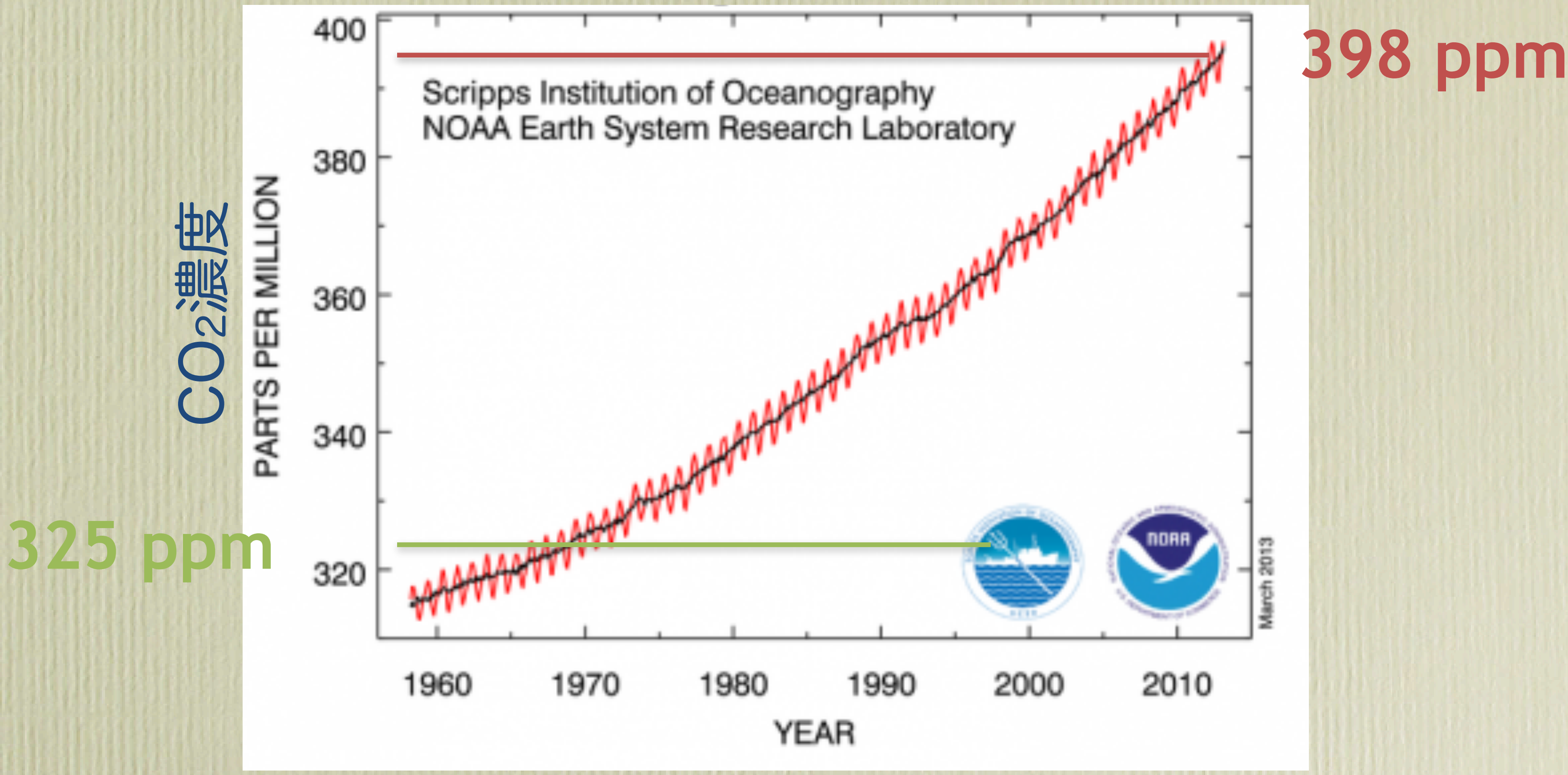
CO_2施肥効果

(CO_2 fertilization effect)

マイナスの効果

気温上昇によって呼吸速度は増加する

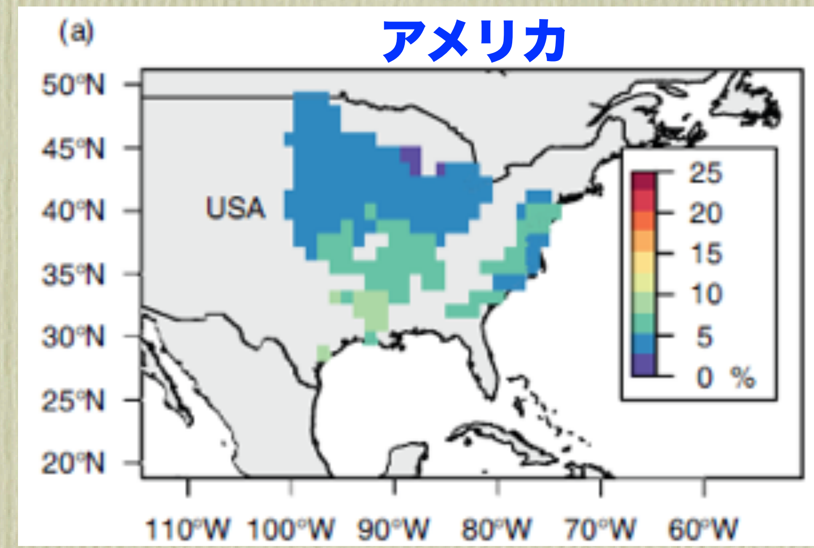
大気CO_2濃度の増加

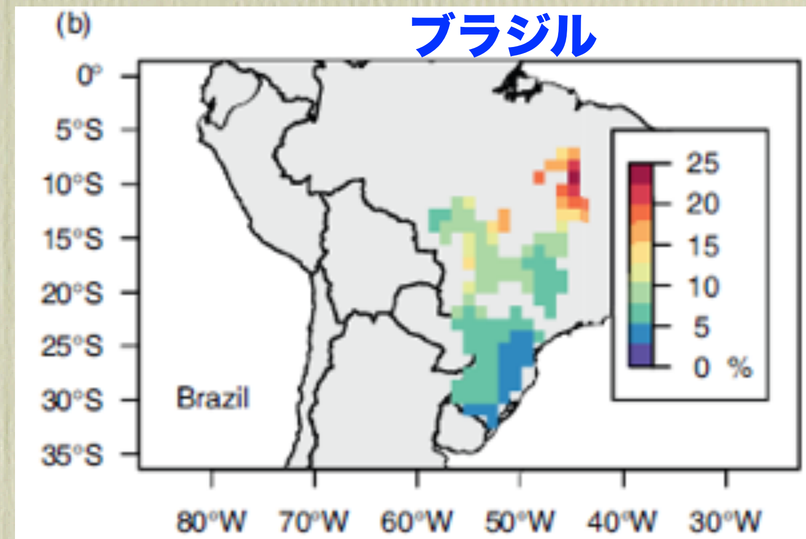


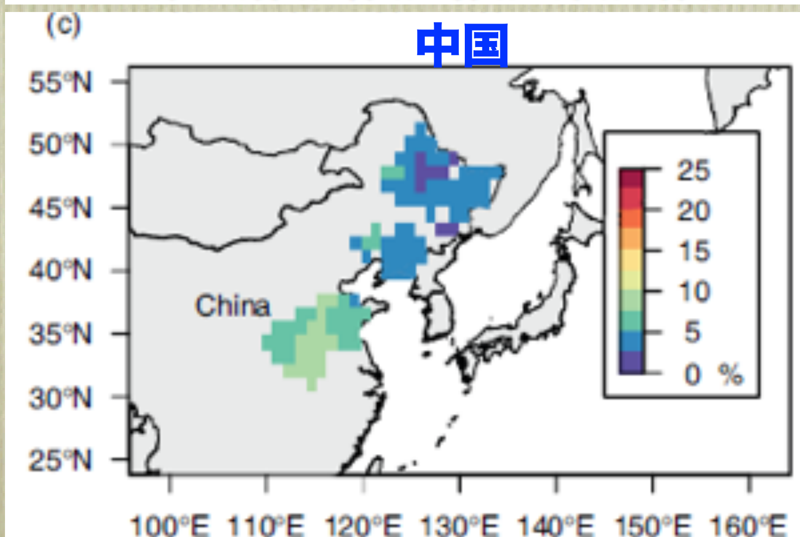
大気中CO_2濃度は年約3%で増加してきた

現在は400ppmを超えている

大豆の主要生産地域における
CO_2施肥効果





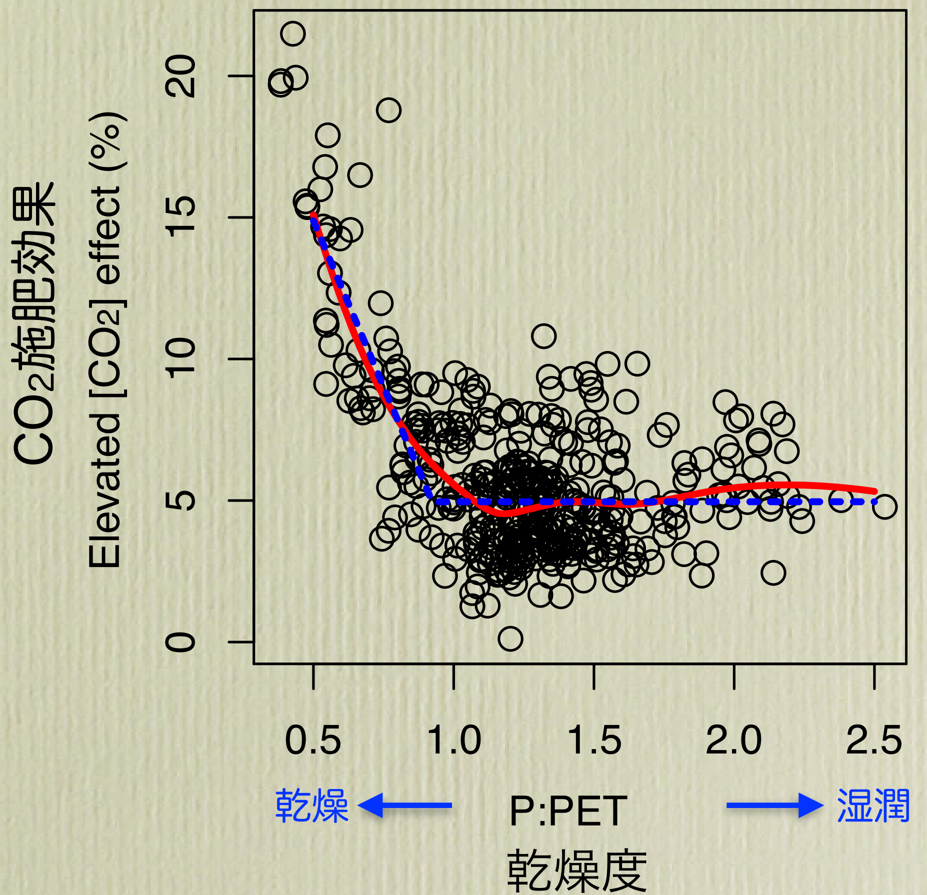


アメリカ：4.34%
ブラジル：7.57%
中国：5.10%
3国平均で約5.8%増加

1980年の収量と2002年〜2006年の平均収量の比

CO_2濃度は約40ppm増加

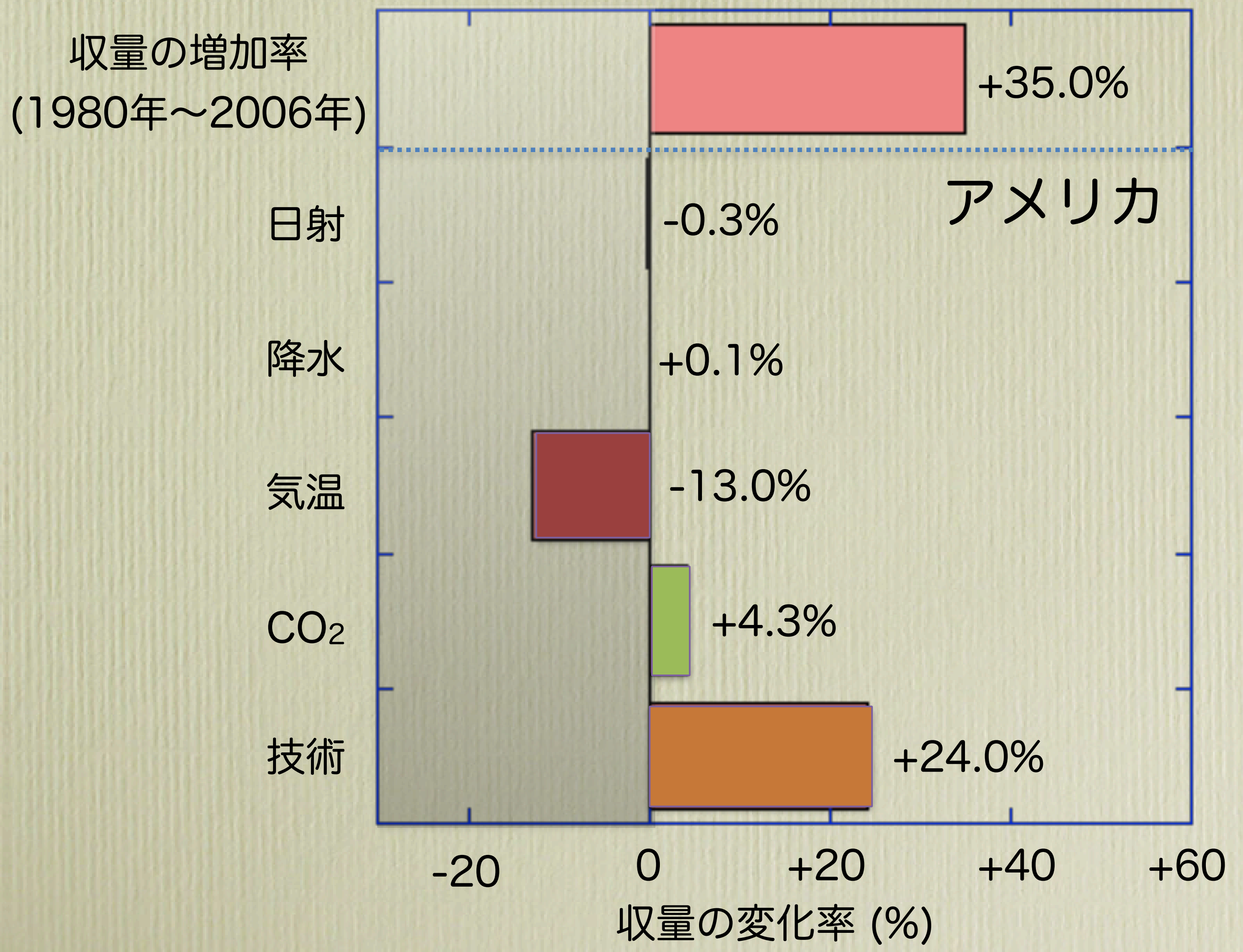
大豆の主要生産地域におけるCO_2施肥効果



乾燥している地域ほどCO_2の施肥効果は大きい

収量に対する要因別の影響

1980年から2006年の間に世界の年平均気温は0.3℃上昇、
CO_2濃度は40ppm上昇した(約12%)。



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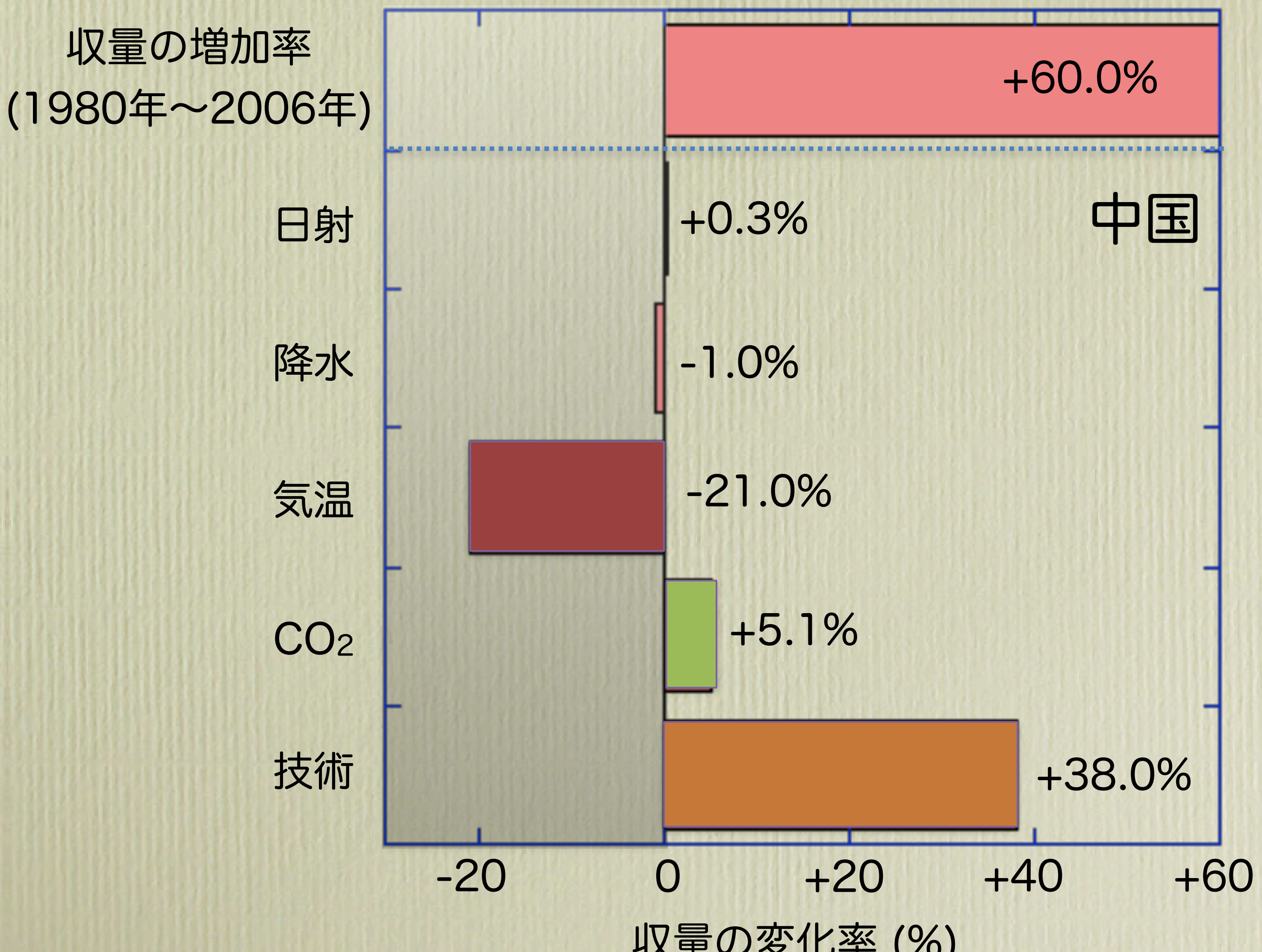

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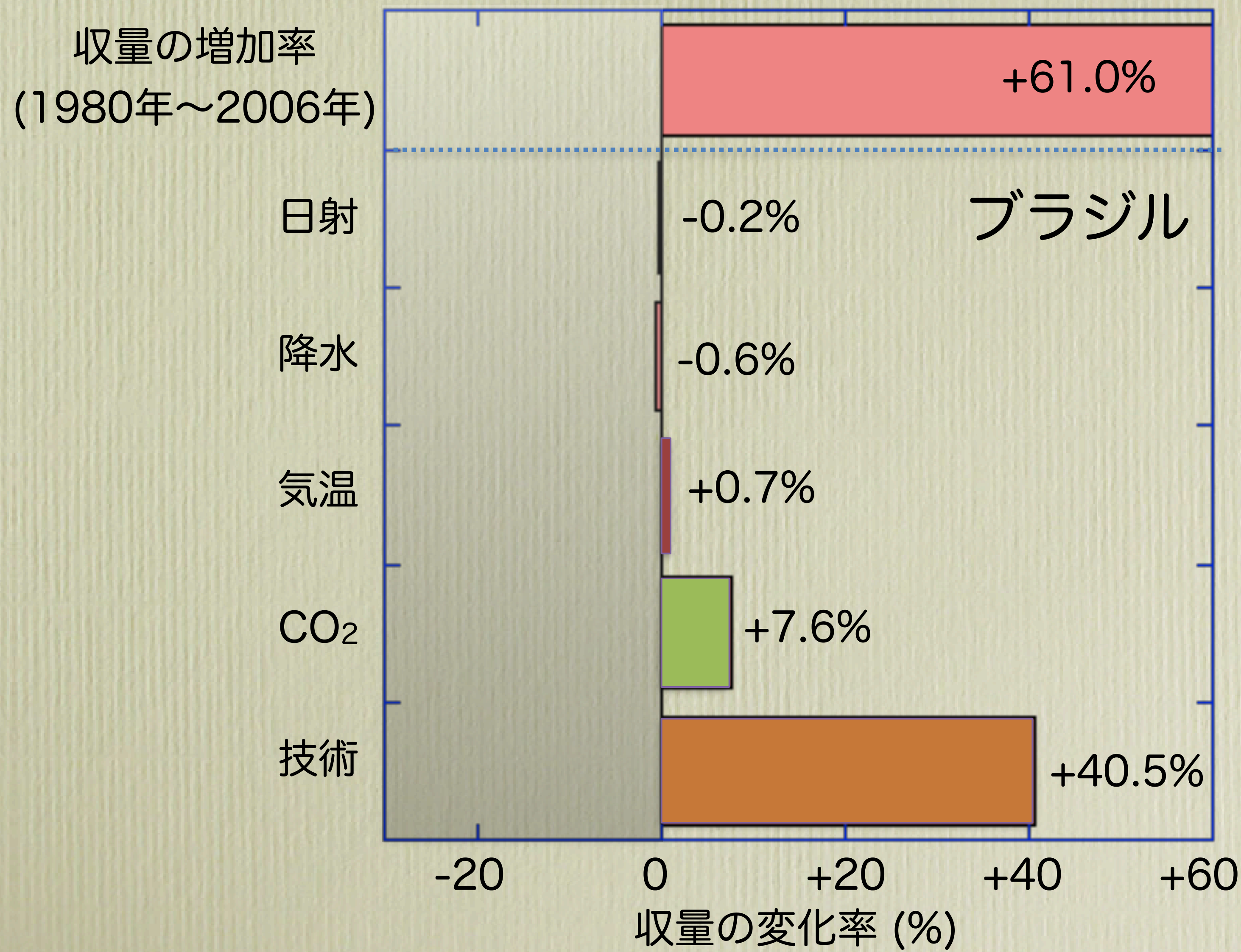

Crop Failure Forecast

- We conducted a global overview of the reliability of crop failure forecasts for maize, rice, wheat and soybean.
- The key question posed was:

How reliable is the forecasting of crop failure at lead times that allow such information to be of value to governments and commercial concerns?

nature climate change

LETTERS

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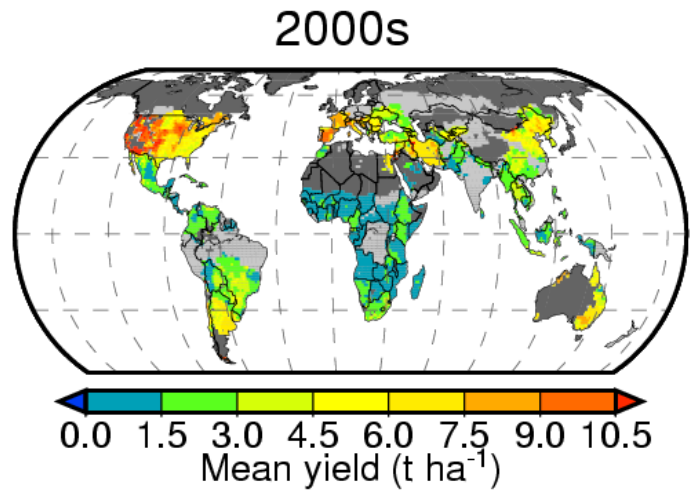
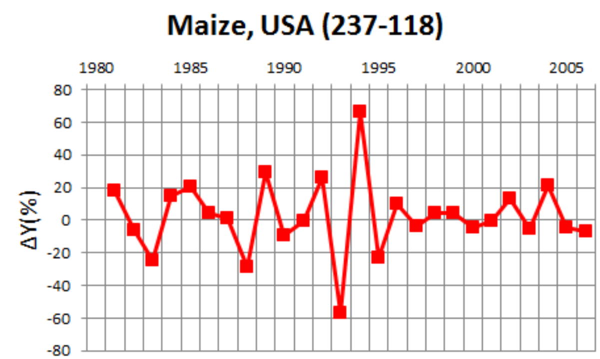
Prediction of seasonal climate-induced variations in global food production

Toshichika Iizumi[1]*, Hirofumi Sakuma[2,3], Masayuki Yokozawa[1], Jing-Jia Luo[4], Andrew J. Challinor[5,6], Molly E. Brown[7], Gen Sakurai[1] and Toshio Yamagata[3]

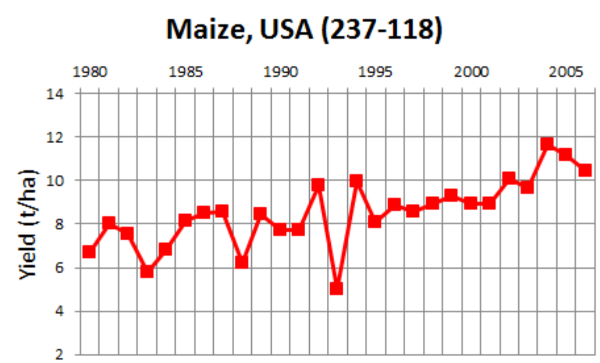
Data and Methods (crop yield)



- Global, gridded historical yield dataset (Iizumi et al., *Global Elol. Biogeogr.*, in review)
  - covers the period 1982-2006
  - derived by aligning county yield statistics with yield proxy from satellites



- Removal of technological yield trend to derive climate-crop relationship
  - $\Delta Y_t = (Y_t - Y_{t-1}) / Y_{ave} * 100$
  - Same average yield was used for the first 3-yr of the study period
  - Popular in Agro-meteorological fields (e.g., Lobell & Field, 2007, *Environ. Res. Lett.*; Kucharik, 2008, *Agron. J.*)



Data and Methods (crop phenology)

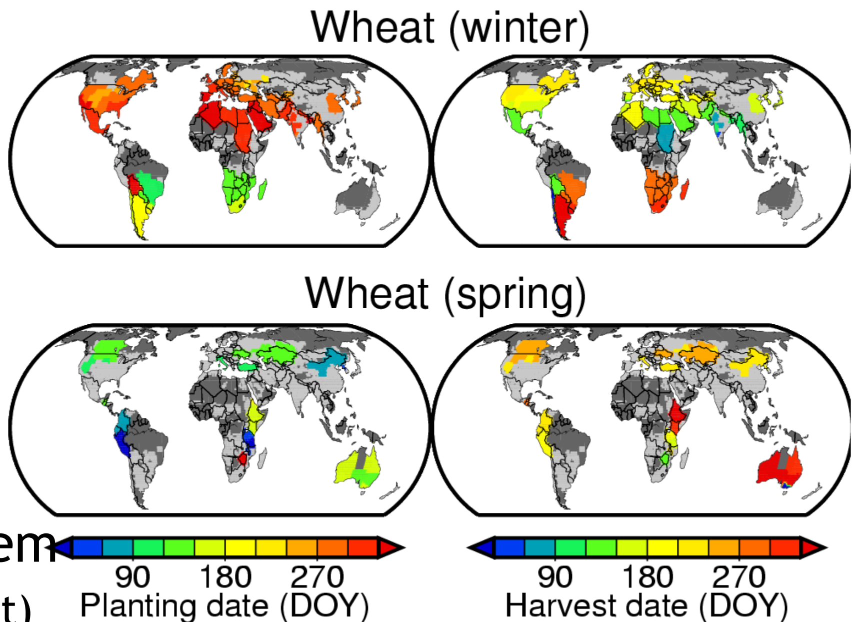
- Global crop phenology dataset

  Sacks et al., 2011, *Global Ecol. Biogeogr.*

  – Type of cropping system
    - Maize (major/secondary)
    - Soybean (major)
    - Rice (major/secondary)
    - Wheat (winter/spring)

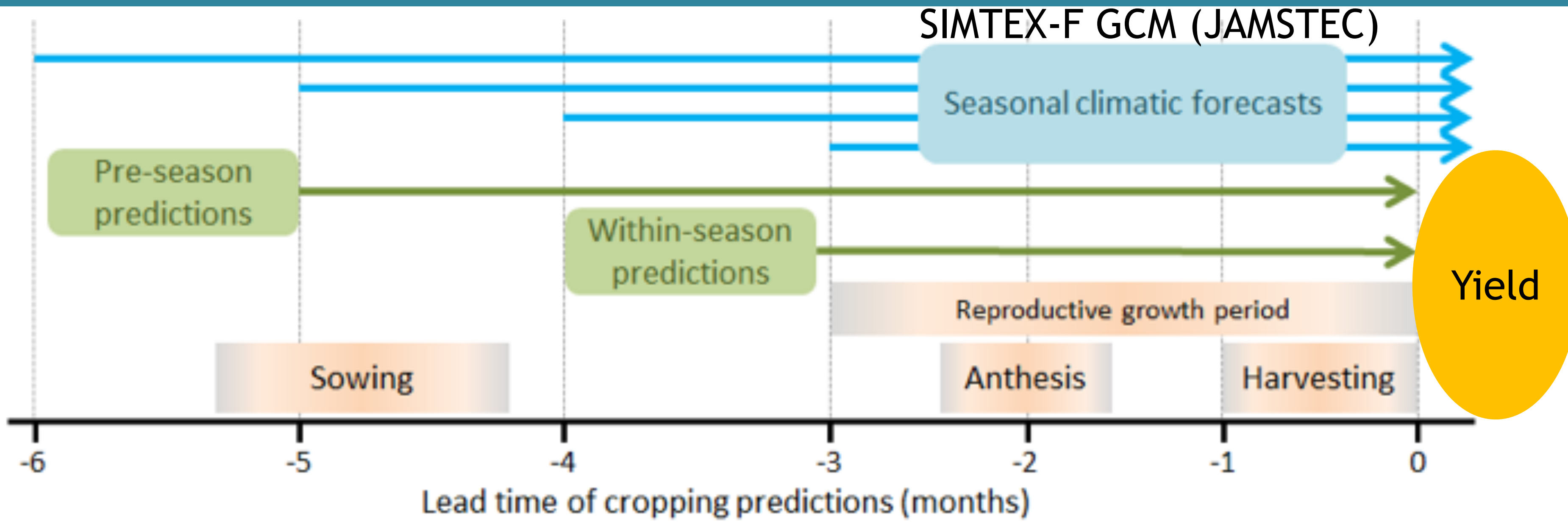
  – Share of production by cropping system
    - Average yield of winter wheat 2 t/ha (100t) and spring wheat 4 t/ha (500t) is not 3 t/ha, but 3.7 t/ha

  – Specification of key growing season for each cropping system



Winter wheat						Spring wheat					
Tillage	Vegetative		Reproductive growth			Tillage	Vegetative		Reproductive growth		
	Plantin		Flowerin		Harvestin		Plantin		Flowerin		Harvestin
Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May
			Key growing season						Key growing season		

Yield Predictions Based on Seasonal Climatic Forecasts



- Pre-season yield predictions employ climatic forecasts with lead time of 3-5 months and provide information on variations in yield for the coming cropping season.
- Within-season yield predictions update the pre-season predictions using climatic forecasts with lead time of 1-3 months.

Statistical Crop Model

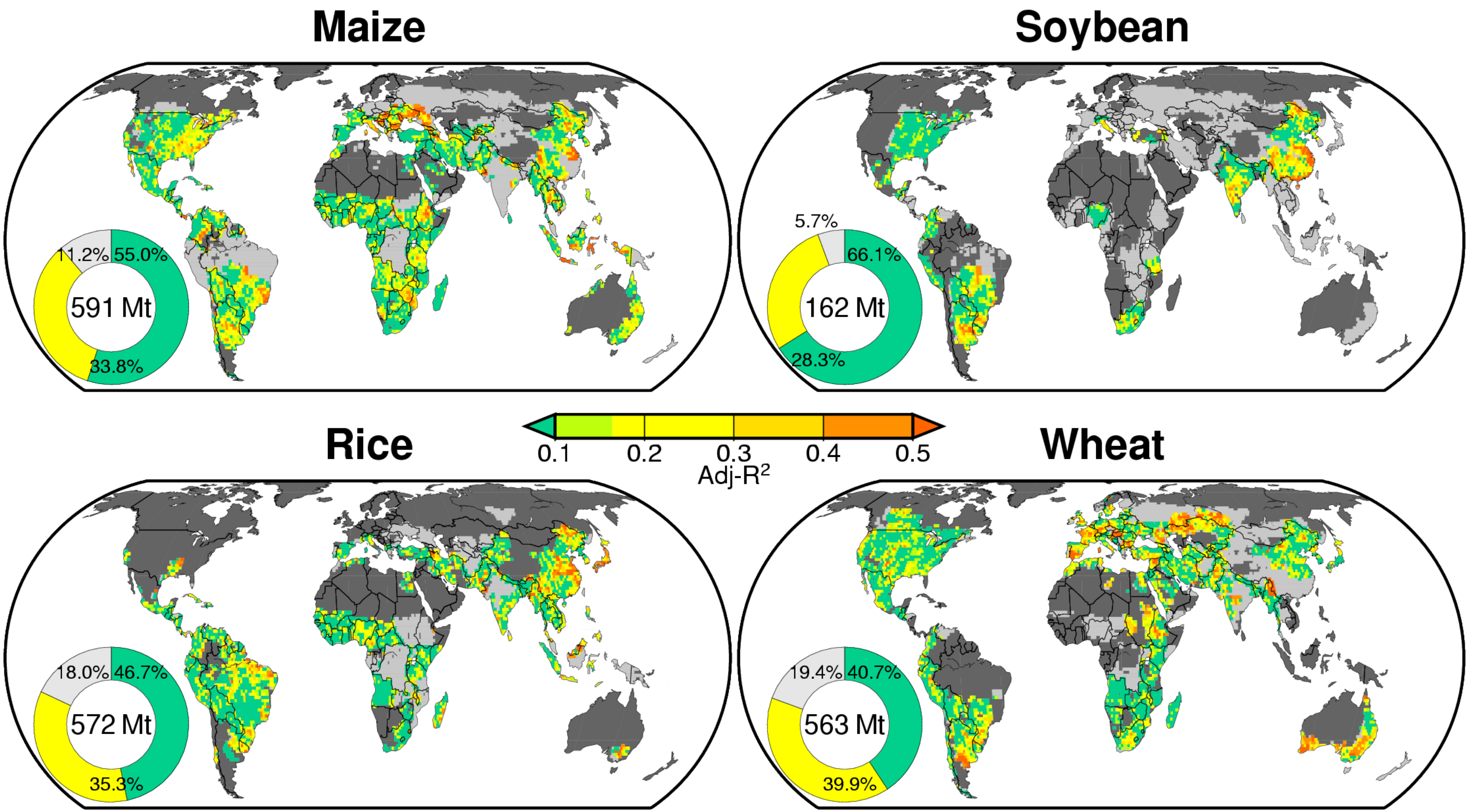
We developed a spatially explicit global dataset of historical yields for maize, soybean, rice, and wheat to explore the year-to-year variation in yields for the period 1982–2006.

Yearly time series of cropping and climatic data were combined to derive multiple linear regression models: first-difference time series in yield (ΔY), temperature (ΔT) and soil water content (ΔSW)

A multiple linear regression model was computed for each cropping system of a crop of interest:

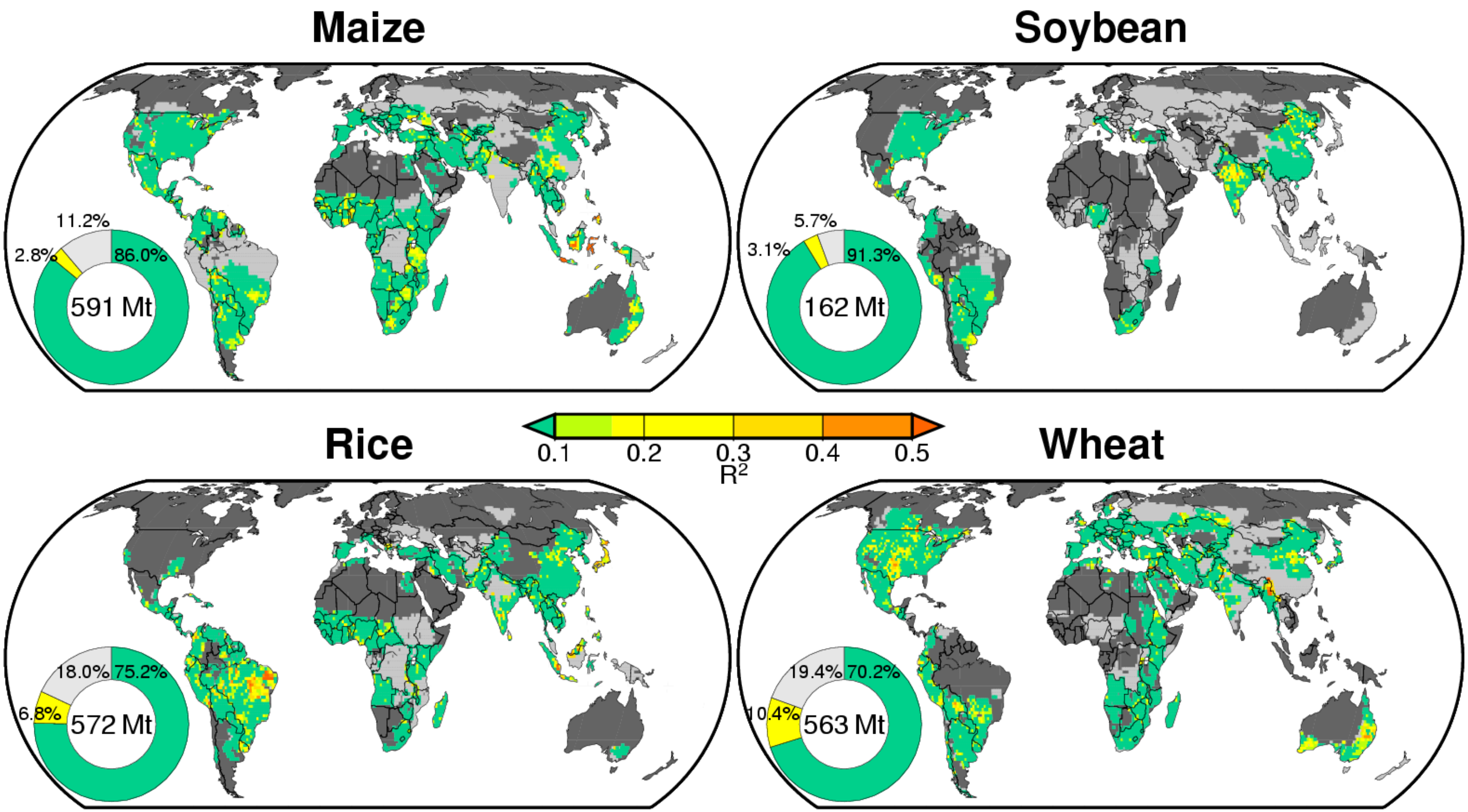
$$\Delta Y = a\Delta T + b\Delta SW + c + \epsilon$$

Hindcasts with reanalysis (upper limit of skill)



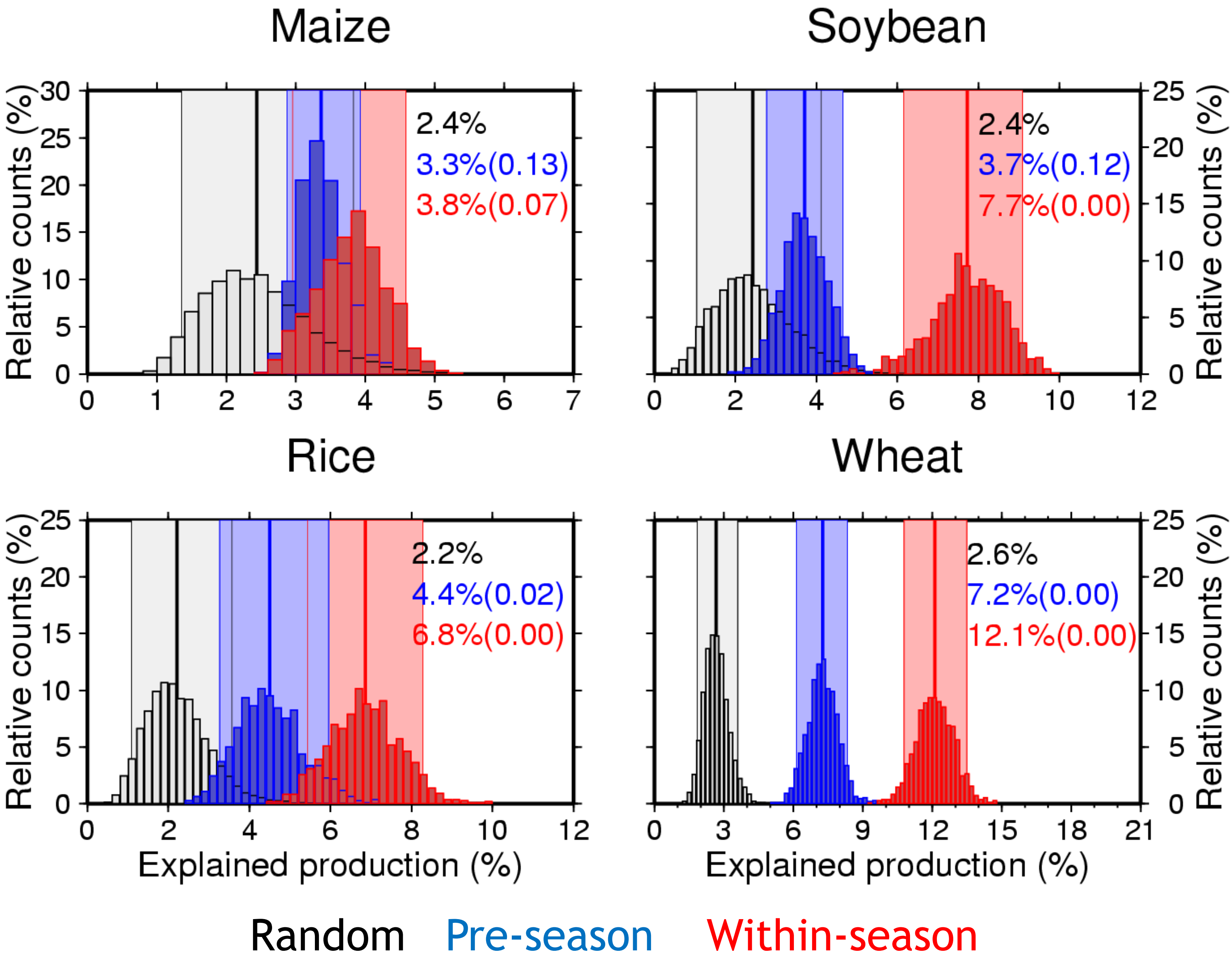
- Over 16% (r=.404, p<.05) of year-to-year yield variation can be explained by temperature and soil moisture alone. Such "skillful" area produces 28 to 40% of world production in 2000.

Within-season prediction

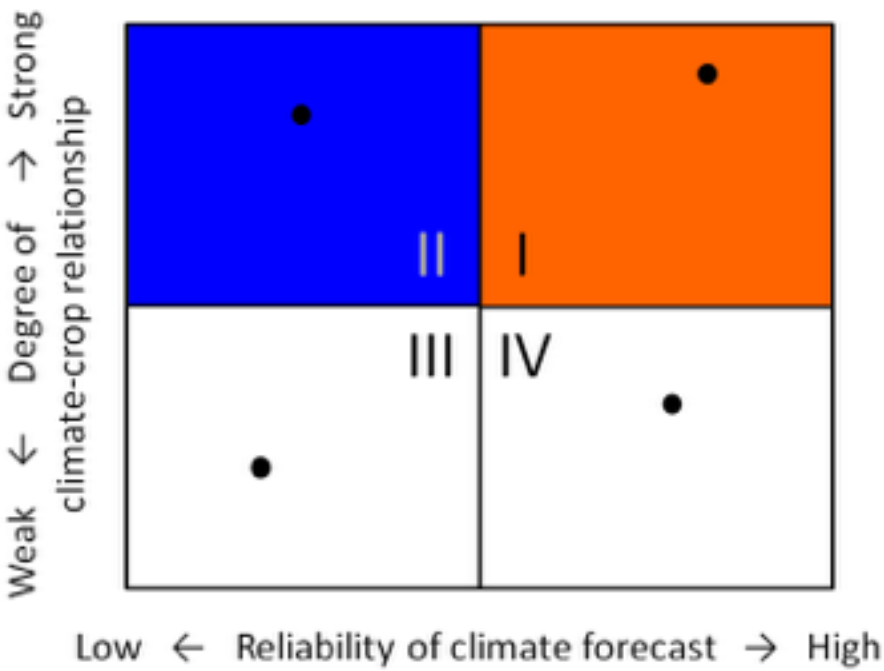


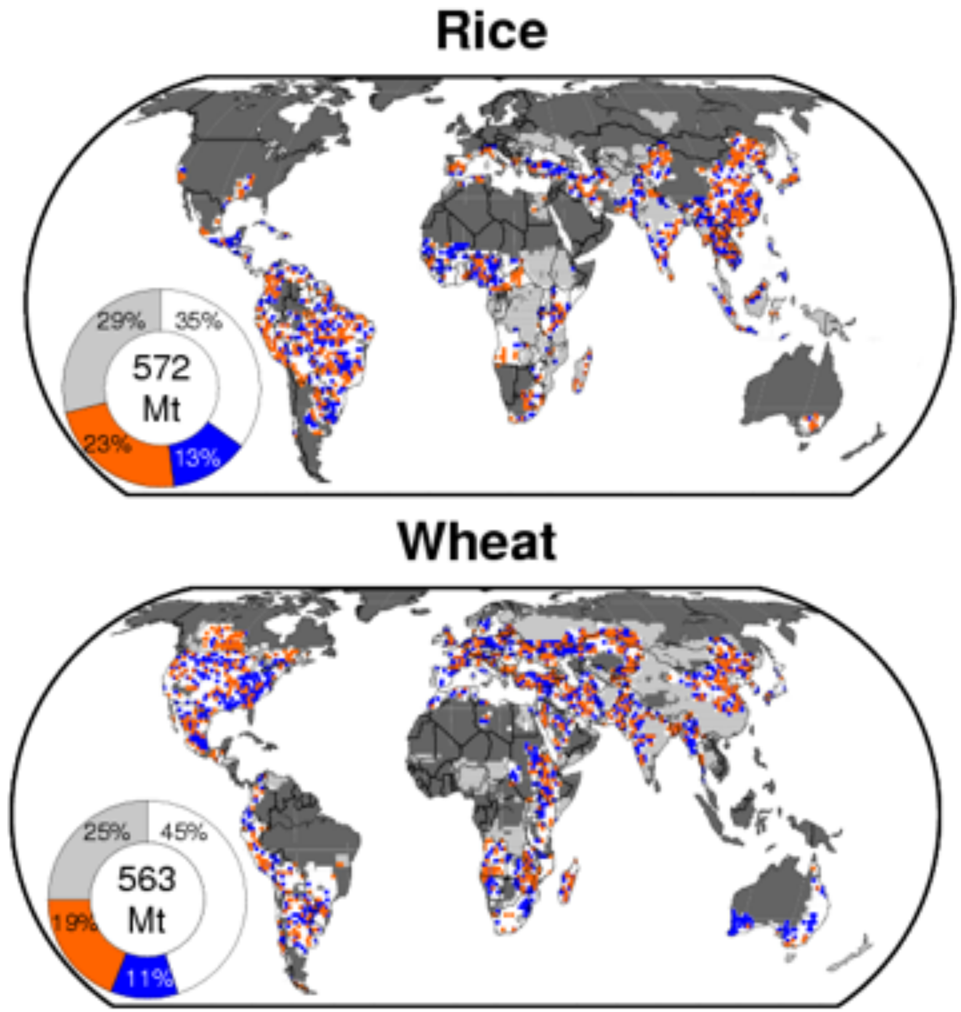
- Skillful area of within-season prediction produces 3 to 10% of world production.
- Prediction achieved limited part of the potential…
- Amount of production produced in "skillful" area decreases as lead time increases.

Are these predictions better than random?



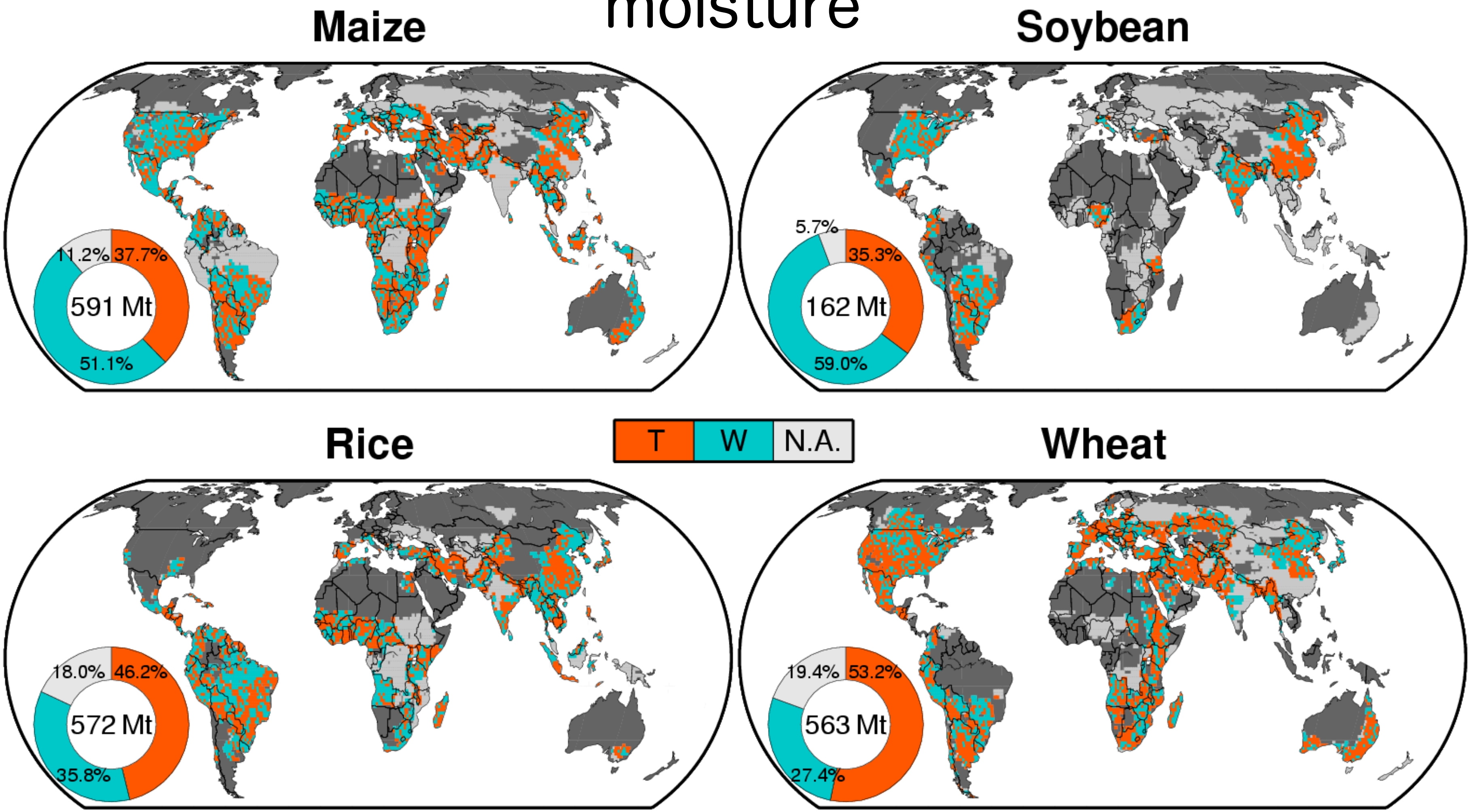
Evaluation of the Reliability of Within-Season





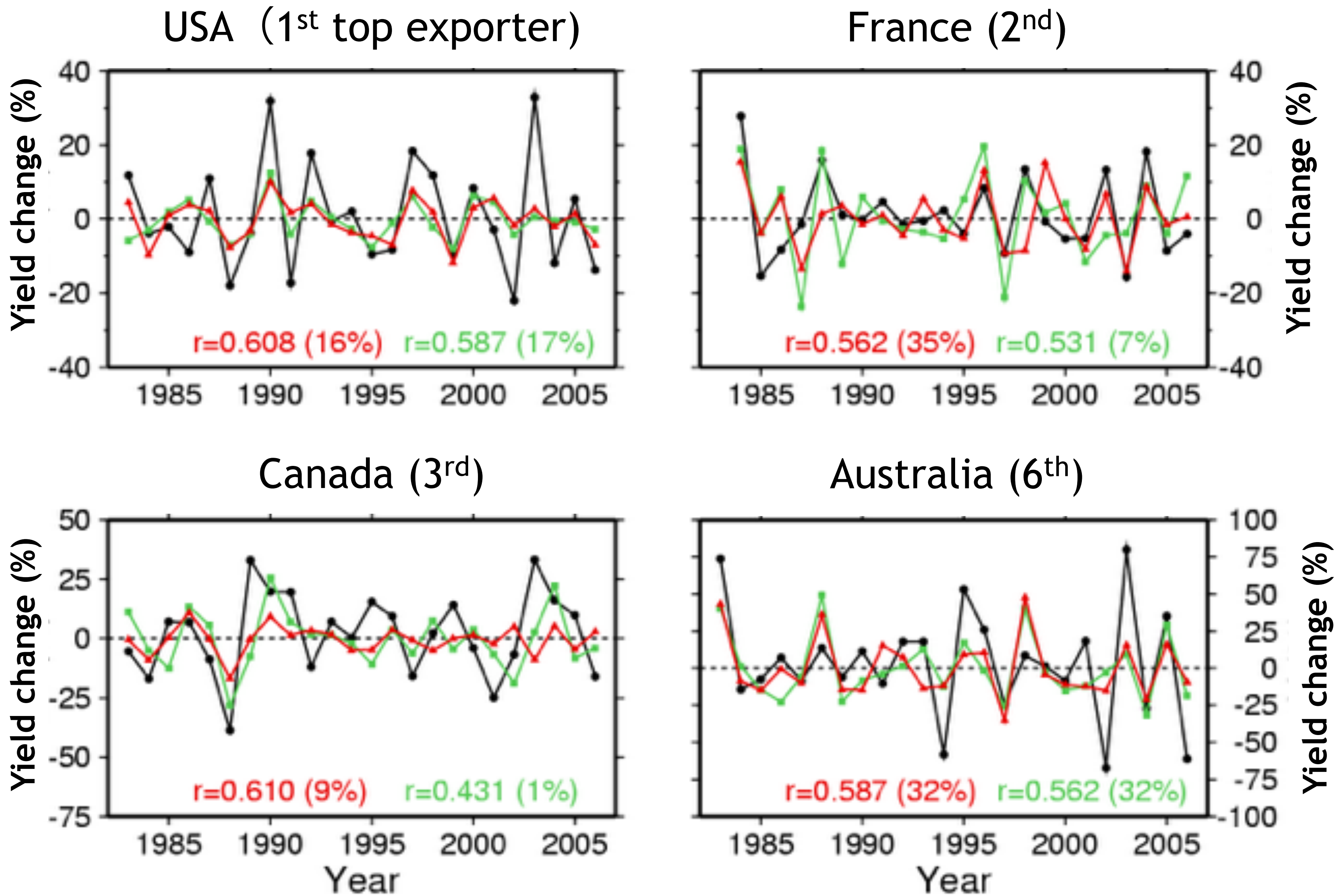
- Moderate-to-marked (5% more) yield losses of rice and wheat over 18-19% of the global harvested area of the crops (correspond to 19–23% of the global production) can be reliably predicted at 3 months before the harvest using within-season prediction.

Sensitivity of yield to temperature and soil moisture



- Weighted average of yield elasticity to temperature and soil moisture (evaluated based on climatological mean values);
- Maize and soybean are water dependent while rice and wheat are more temperature dependent.

Reliability of Wheat Predictions for Exporting



Obs./Within-season/Pre-season

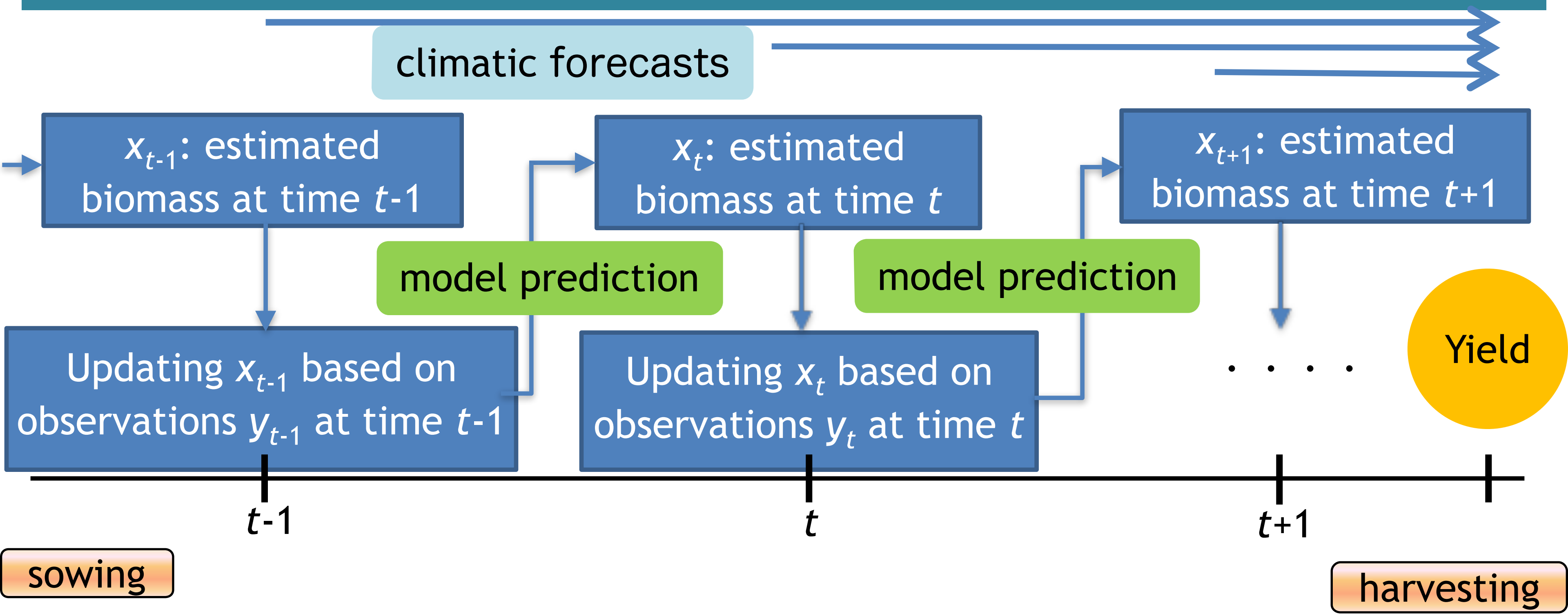
Correlation (Percentage of reliably-predicted area to total harvested area of a crop in a country)

Remarks

- Crop failures of rice and wheat over a substantial percentage (19–23%) of the global harvested area of these crops can be reliably predicted at 3 months before the harvest.

- The percentages of harvested area (production) of the crops where crop failures of the crops are reliably predictable can increase to 30-33% (31-40%) if climatic forecasts are near perfect.

Further Study: Nowcasting for Food Security



- Nowcasting encompasses a description of the current state of the crops and the prediction of how the crops will grow during the next stage and how much yield harvested.
- The current state of crops is updated with observations.

世界の食料生産予測における課題

気候変動予測の不確実性

・短期（季節予報〜数年）と長期の予測の不確実性

・極端現象

・モデルの検証と予測に必要なデータの収集

作物の環境応答の不確実性

・作物の高CO_2応答などにおけるモデルの不確実性

・作物収量のポテンシャル（収量はどこまで増加するのか）

・極端現象に対する応答

社会システムの不確実性

・土地利用変化

・ライフスタイルの変化

・バイオエネルギーとの競合