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science for global insight

Robust management of water-energy-food-… nexus under uncertainties, systemic risks and resource constraints

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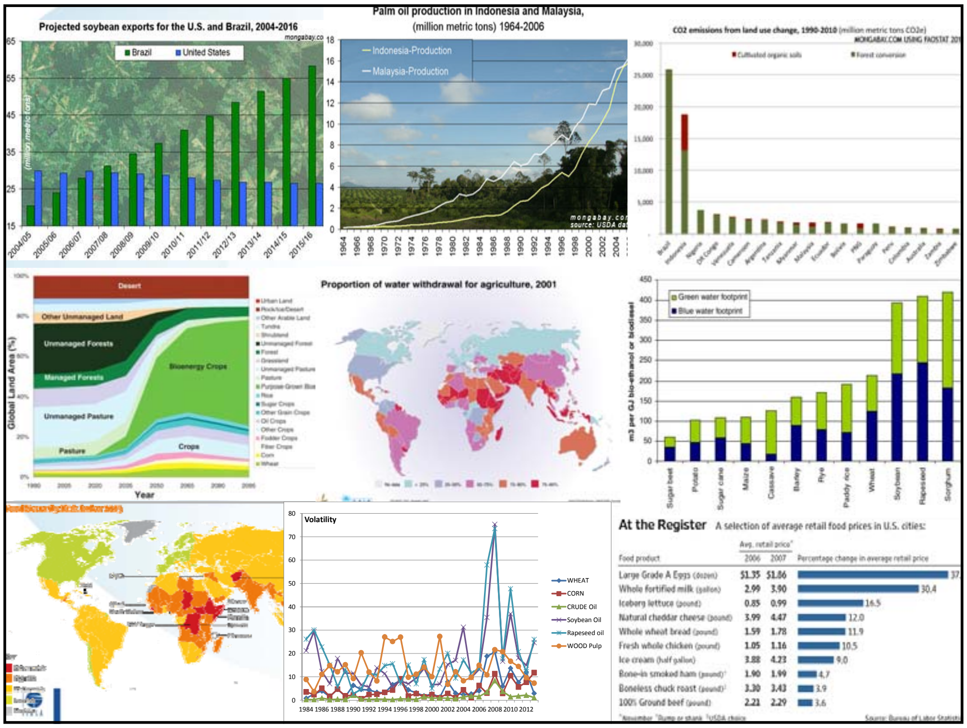
Motivations

- **Global changes increase interdependencies in** Food-Water-Energy (FWE) systems
  - increased population, demands for food, feed, fiber
  - Trade policies, markets globalization
  - weather variability and climate changes
- **Systemic risks (SR) affect security of FWE**
  - Emergency of new type of dependent systemic risks (SR)
  - SRs depend on (intentional and unintentional) decisions of agents, natural calamities
    - agric. prices increase in Europe due to natural disasters, yield shocks in Australia, Kazahstan, Russia
    - floods due to wrong dike, levees, flood walls maintanance, e.g., 80% of flooding after Katrina
    - blackouts in energy grids, e.g., New York 2003, 50 mill ppl without power and communication
    - biofuels production, e.g., insecurity of FWE systems
    - risks are spatially and temporary explicit, multi-variate, multiagent, multisystem
- **Transformations in land use systems (LUS)**
  - land transformations, e.g., from natural/forest to agricultural land
  - structure and intensity of production, e.g., from rainfed to irrigated, from food to energy crops
- **Examples**
  - deforestation in Brazil and Indonesia due to biofuels targets, livestock demands
    - 1990-2010, 90% palmoil plantations in Indonesia are from deforestation; 880 thd ha of tropical peatla
  - 580000 sq km of Amazon forests are destroyed in Brazil since 1980
    - due to clearing for cattle pastures (90 mill hd of cattle, up from 26.6 mill in 1990

    The Brazilian Amazon has more than 214,000 square mls of pasture, space larger than France
    - expansion of cash crops agriculture (in particular, soy production)
    - expansion of land colonization and subsistence farming, …

  increased emissions (45b tons CO2 in 20 years) due to deforestation (Indonesia&Brazil)

  incresed prices for food and feed due to cash crops production, linkages of biofuel and crude oil markets



Traditional approaches

- **Disintegrated analysis of FWE systems**
  - Energy models
  - Estimation of (biofuels) agricultural production without accounting for:
    - other systems' constraints and demands for natural resources, e.g. water, land
    - biofuels introduced dependence of agricultural markets on crude oil markets, the so-called „price volatility" NEXUS

- **Integrated assessment models assume certainty about systems and agents**
  - Deterministic input-output-based analysis (popular in crosssectoral planning), certainty about resources, demands, costs, input-output coefficients, etc.
  - Life-cycle analysis (used, e.g., for bioenergy analysis)

- **Deterministic (average) models – no long-term planning of strategic decisions**
  - Scenario-dependent solutions lead to lock-in states and irreversibilities if other scenario occures
  - Not-diversified, degenerated „corner" solutions, cheapest or most profitable alternatives are selected
  - No possibility to „reverse" or adjust decisions when information about uncertainties becomes known

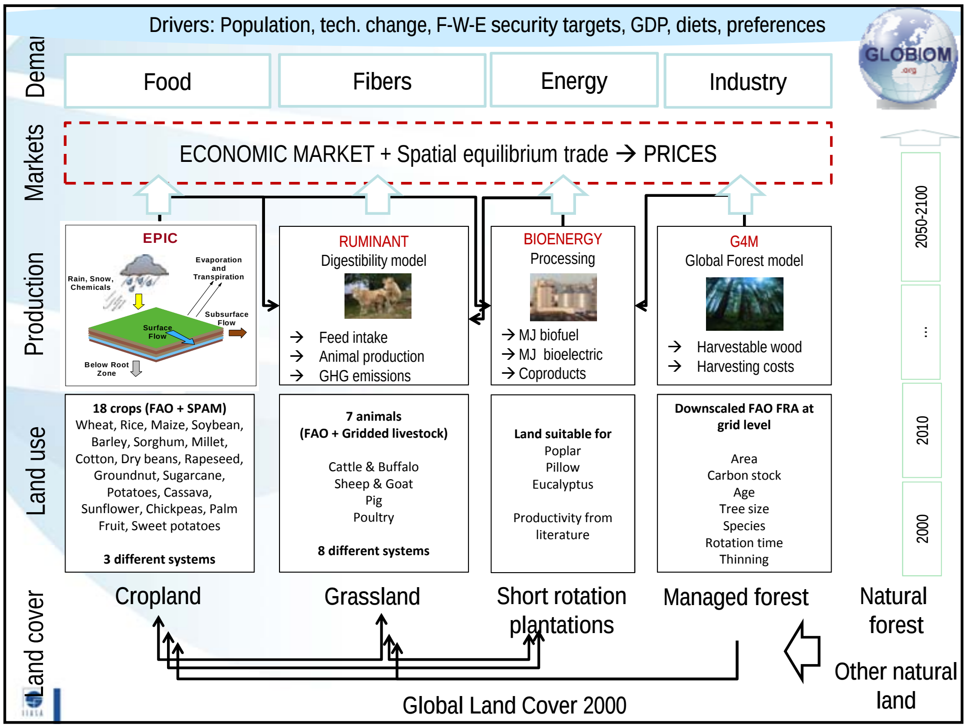
- **Not addressing interdependent systemic risks**
  - Independent risks (e.g. insurance models)
  - Traditional models use average indicators
    - Actuarial „average"- based risk-pricing models are wrong
    - The law of large number does not work – pooling of dependent risks increases insecurity
    - NPV - discounting rate equals average market return

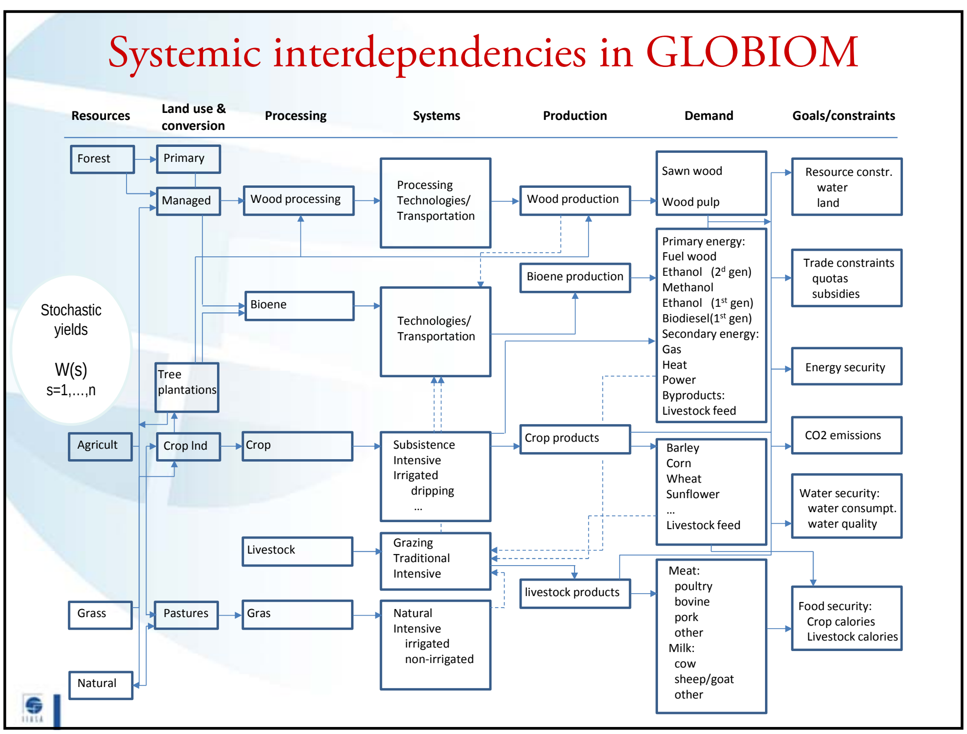
Main challengies

- **Global-local modeling of interdependent systems & systemic risks**
  - Propagation of risks, multivariate, multisystem, multiagent, spatially and temporary dependent risks
  - Risks are „shared“, often - magnified by interdependencies (e.g. trade), (resource) constraints, targets
  - Systemic failures and catastrophic losses may be caused by a peripheral event
- **Robust decisions (RD) instead of „exact“ prediction**
  - Robust decisions leave us better-off independently of what uncertainty scenario realises
- **Joint design of strategic ex-post long-term vs adaptive operational decisions**
  - Strategic (irreversible) are taken before uncertainty scenario realizes
  - Adaptive scenario-dependent are taken after the scenario becomes known
- **RDs lead to systems analysis (SA) instead of analysis of existing systems**
  - Inclusion of new nonexisting technologies, financial instruments, crops portfolios
  - Design of new systems
- **RDs rely on quantile-based instead of average indicators**

Methods, models, DSSs

- **Integrated (stochastic) modeling at different scales**
  - **Global stochastic GLOBIOM – LUS model, food-water-energy-environ NEXUS**
- **Robust probabilistic downscaling for linking global and local models**
  - **Stochastic GLOBIOM + prob downscaling: food-water-energy-environmental security project, IIASA-NASU, Ukraine**
- **Linkage** of sectorial models
  - GLOBIOM + MESSAGE + GlobWater
  - Water-agricultural-energy-environmental model, China
  - Integrated robust management of food-energy-water-land use nexus for sustainable development, joint IIASA-NASU, Ukraine
- **Uncertainties, variability, risk: strategic DSSs involve long-term strategic and short-term operational two-stage planning**


Drivers: Population, tech. change, F-W-E security targets, GDP, diets, preferences
Demand
Food
Fibers
Energy
Industry
GLOBIOM
Markets
ECONOMIC MARKET + Spatial equilibrium trade → PRICES
Production
EPIC
Rain, Snow, Chemicals
Evaporation and Transpiration
Surface Flow
Subsurface Flow
Below Root Zone
RUMINANT
Digestibility model
→ Feed intake
→ Animal production
→ GHG emissions
BIOENERGY
Processing
→ MJ biofuel
→ MJ bioelectric
→ Coproducts
G4M
Global Forest model
→ Harvestable wood
→ Harvesting costs
2050-2100
...
2010
2000
Land use
18 crops (FAO + SPAM)
Wheat, Rice, Maize, Soybean, Barley, Sorghum, Millet, Cotton, Dry beans, Rapeseed, Groundnut, Sugarcane, Potatoes, Cassava, Sunflower, Chickpeas, Palm Fruit, Sweet potatoes
3 different systems
7 animals
(FAO + Gridded livestock)
Cattle & Buffalo
Sheep & Goat
Pig
Poultry
8 different systems
Land suitable for
Poplar
Pillow
Eucalyptus
Productivity from literature
Downscaled FAO FRA at grid level
Area
Carbon stock
Age
Tree size
Species
Rotation time
Thinning
Land cover
Cropland
Grassland
Short rotation plantations
Managed forest
Natural forest
Other natural land
Global Land Cover 2000


Systemic interdependencies in GLOBIOM
Resources
Land use & conversion
Processing
Systems
Production
Demand
Goals/constraints
Forest
Primary
Managed
Wood processing
Processing Technologies/ Transportation
Wood production
Sawn wood
Wood pulp
Resource constr. water land
Primary energy: Fuel wood Ethanol (2d gen) Methanol Ethanol (1st gen) Biodiesel(1st gen) Secondary energy: Gas Heat Power Byproducts: Livestock feed
Bioene production
Trade constraints quotas subsidies
Stochastic yields
W(s) s=1,...,n
Bioene
Technologies/ Transportation
Energy security
Tree plantations
Agricult
Crop Ind
Crop
Subsistence Intensive Irrigated dripping ...
Crop products
CO2 emissions
Barley Corn Wheat Sunflower ... Livestock feed
Water security: water consumpt. water quality
Livestock
Grazing Traditional Intensive
livestock products
Meat: poultry bovine pork other Milk: cow sheep/goat other
Food security: Crop calories Livestock calories
Grass
Pastures
Gras
Natural Intensive irrigated non-irrigated
Natural

Stochastic GLOBIOM: goal function

Maximize welfare

$$\mathrm{E}\left(\begin{array}{l}\sum\left[\int \varphi^{demd}_{r,t,y}\left(D_{r,t,y}(\omega)\right)\mathrm{d}(\cdot)\right]-\sum_{r,\tilde{r},y}\left[\int \varphi^{trad}_{r,\tilde{r},t,y}\left(T_{r,\tilde{r},t,y}(\omega)\right)\mathrm{d}(\cdot)\right]\\ -\sum_{r}\left(\tau^{live}_{r}\cdot B(\omega)_{r,t}\right)-\sum_{r,m}\left(\tau^{proc}_{r,m}\cdot P_{r,t,m}(\omega)\right)-\sum_{r,e}\left(\tau^{emit}_{t,e}\cdot E_{r,t,e}(\omega)\right)\end{array}\right)$$

$$-\sum_{r}\left[\int \varphi^{splw}_{r,t}\left(W_{r,t}\right)\mathrm{d}(\cdot)\right]$$

$$-\sum_{r,l,\tilde{l}}\left[\int \varphi^{lucc}_{r,l,\tilde{l},t}\left(\sum_{c,o,p,q} X_{r,t,c,o,p,q,l,\tilde{l}}\right)\mathrm{d}(\cdot)\right]$$

$$-\sum_{r,c,o,p,q,l,b,m}\left(\tau^{land}_{c,o,p,q,l,b,m}\cdot X_{r,t,c,o,p,q,l,b,m}\right)$$

Land allocation, irrigation capacities, etc., are strategic long-term variables

Demand, trade flows, storage withdrawals, etc., are stochastic scenario-dependent operational (adaptive) variables

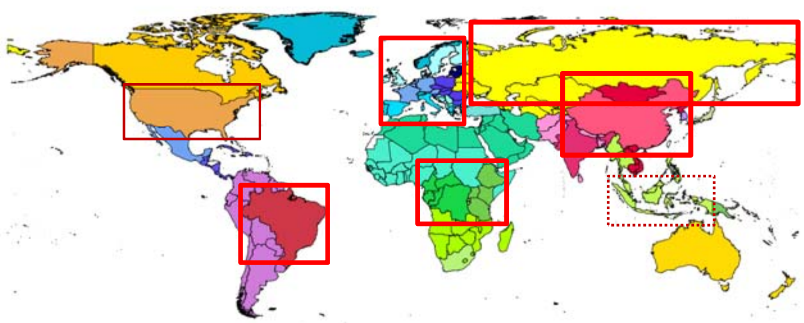
Production balance $P\left(D_{r,t,y}(\omega)\le Production_{r,t,y}(X,\omega)+\sum_{\tilde{r}} T_{\tilde{r},r,t,y}(\omega)-\sum_{\tilde{r}} T_{r,\tilde{r},t,y}(\omega)\right)\le p_{r,t,y}$

Food security $P\{D_{r,t,F}<D^{*}_{r,t,F}\}\le p_{r,t,F}$

Environment security $P\{E_{r,t,e}>E^{*}_{r,t,e}\}\le p_{r,t,e}$

Bio-energy security $P\{D_{r,t,Be}<D^{*}_{r,t,E}\}\le p_{r,t,Be}$

A global model with the possibility to zoom into a region or a country



30 Regions are interconnected through international trade

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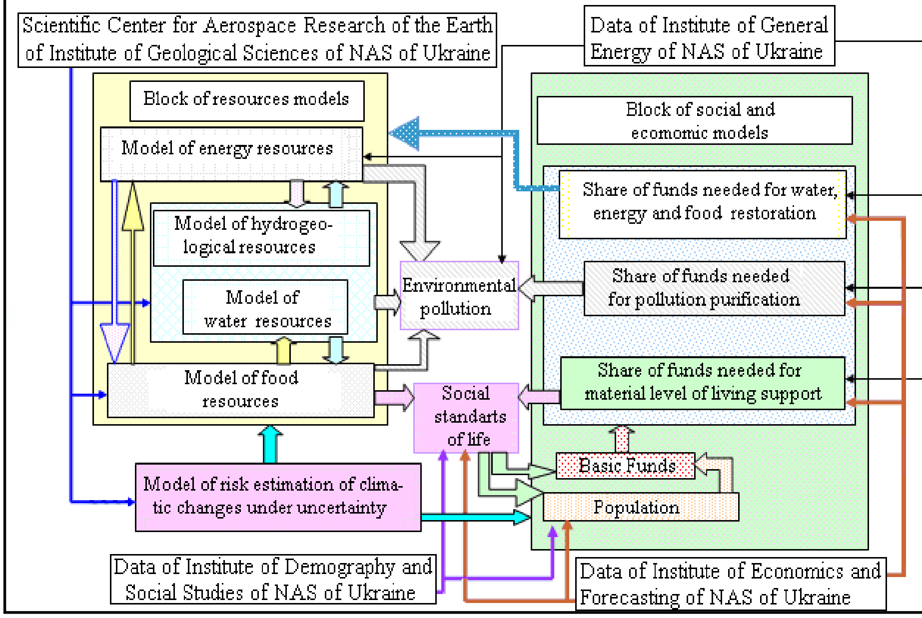
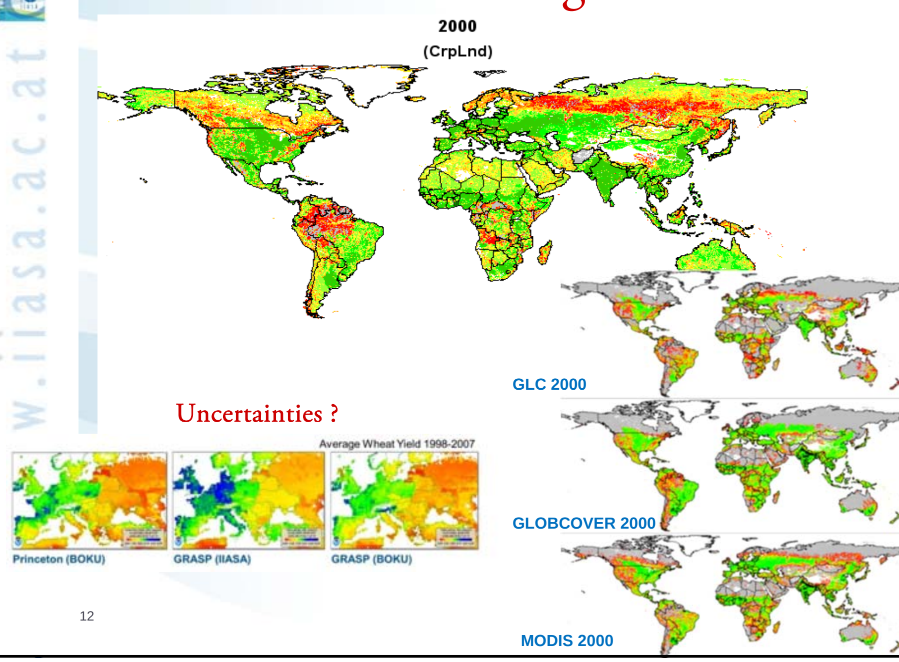
Global-local NEXUS, IIASA-NASU FWEES security project



… downscale into grid cells



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Robust probabilistic downscaling

A set of priors $Q = \{q^s, s = \overline{1:S}\}$ defines alternative feasible distributions, i.e. scenarios of yields or different land use maps

The goal is to minimize the information distance with respect to the set Q i.e. minimize *F(z):*

$$F(z) = \max_s \sum_{i,j} z_{ij} \ln(z_{ij} / q_{ij}^s) = \sum z_{ij} \ln(z_{ij} / q_{ij}^s(z))$$

$$F(z) = \max_\gamma \sum_s \gamma_s \sum_{i,j} z_{ij} \ln(z_{ij} / q_{ij}^s)$$

$$\sum_{s=1}^S \gamma_s = 1 \qquad \gamma \in H$$

e.g. $\gamma_s \ge \gamma_t \quad \gamma_s + \gamma_t \ge 1/2$ for some *s* and *t*

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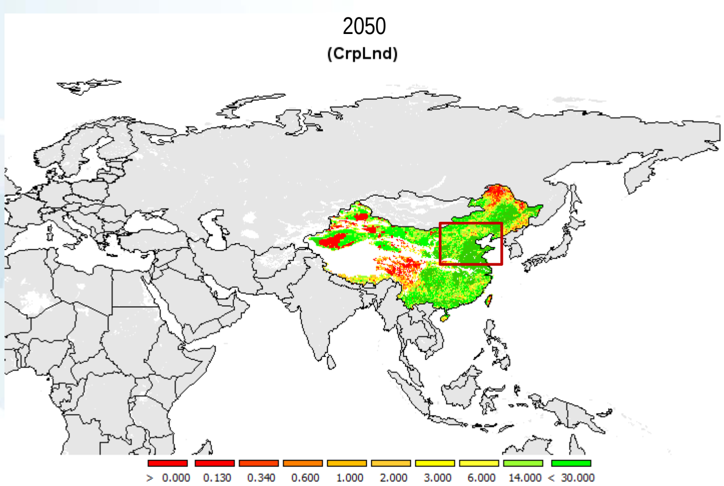
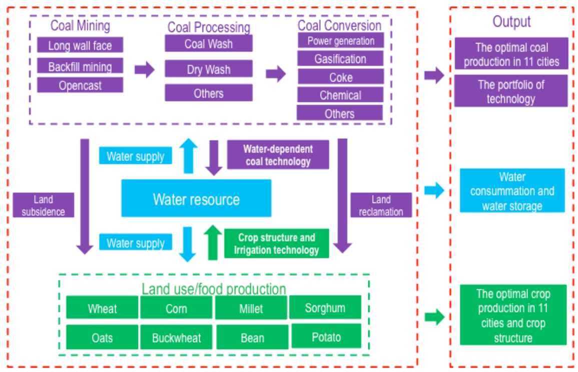
GLOBIOM-SSP downscaling for China: food, water, energy security issues



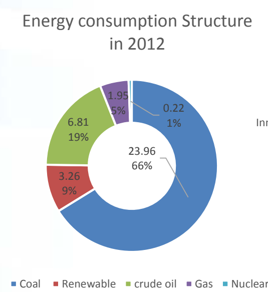
Systemic interdependencies in China-model

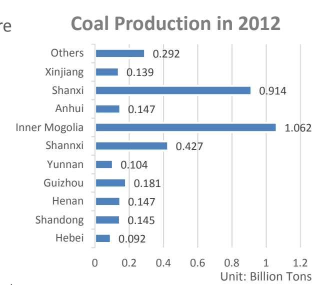
- Coal (for energy, industry, etc) vs. agricultural (crops) production
- Poor water availability
- Competition for land: 40% overlap
- Sector-specific demand constraints on production of each sector
- Joint constraints on water consumption and land use
- Presence of uncertainties related to water availability, weather, markets, etc.

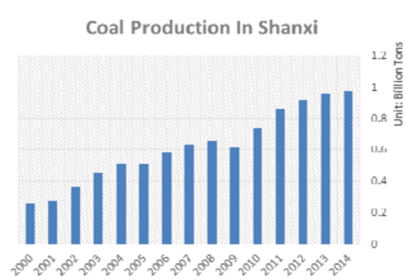


Energy security in China

- ~70% energy consumption in China is coal-based; Shanxi produced 26% of total coal in 2012
- High demand for water
- Serious environmental, social, and economic impacts

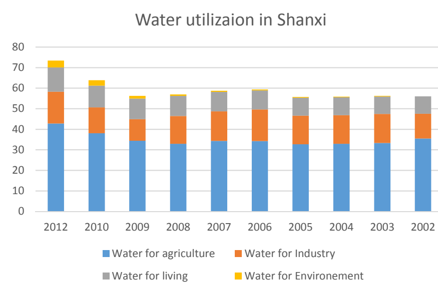






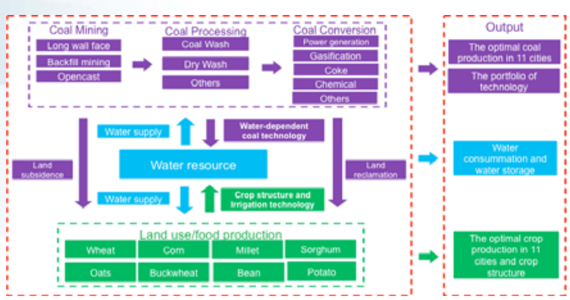
Water security in coal-mining areas

- Mismatch between coal and energy production and water resources
- Competition for water between agricultural production, coal related industry and other water users: coal related industry and agriculture consume almost 80% water
- Further expansion of coal industry could be infeasible under water scarcity
- Variability of water supply and demand



Energy-water-food nexus: uncertainty and security risks

- Energy sector: alternative energy resources (coal, gas, wind, water), production and processing technologies, water saving technologies, etc.
- Agricultural sector: production and resource management technologies, trade, storage
- Resource constraints, variability of water supply
- The need for proper combination of long- and short-term decisions:
  - Long-term: technological portfolio (coal, gas-based technologies; irrigaiton, water saving), water and grain storages, etc.
  - Short-term: trade, prices, subsidies,



The need for robust solutions

- Ex-ante first-stage: water storage capacities, irrigation capacities, land allocation between land uses and crops, technological portfolios, etc.
  - ✓ Ex-ante strategic decisions are implemented before information about water supply scenario (scenarios) becomes available
- ex-post (adjustments) second-stage: water withdrawals, water redistribution/transfer, water and agricultural trade, prices, etc.
  - ✓ Operational ex-post decisions help execute strategic decisions, are implemented after information about water supply scenario (scenarios) becomes available
- The model derives a robust combination of complementary mitigation and adaptation decisions

The integrated two-stage stochastic model

Non-linear Stochastic Model Formulation

- **There are 3 groups of strategic decision variables (first stage) in the model: x_{ijmt} , y_{kjm}, and Z_j.**

And the goal function is as follows:

$$\min_{x,y,z} \sum_{i,j,k,m,t} [C_{ij}^{CP} x_{ijmt} + C_{ij}^{CT} x_{ijmt} + C_{ijt}^{CC} x_{ijmt} + C_{ijt}^{CC} x_{ijmt} + C_{kj}^{AP} y_{kjm} + C_{kjm}^{AT} y_{kjm} + C_j^{inv} Z_j] + \underbrace{\sum_{i,j,k,m,t,w} \gamma_j E[\max\{0, W_{ijt} x_{ijmt} + W_{jk} y_{kjm} - W_j(w) - Z_j\}]}$$

Non-linear non-smoth risk (in-security) function, i.e. (in)security is characterized by shortages of water, coal, crop, etc.

- ➢ x_{ijmt} , y_{kjm} , Z_j are non-negative, stand for coal and crop production and reservoir capacity
- ➢ Where:
- ➢ C_j^{inv} - investment by location j per unit of added water
- ➢ γ_j - the risk parameter (costs or losses) caused by the water shortage in location j per unit of water shortage;
- ➢ $W_j(w)$ - stochastic water supply (from precipitation, ground water, etc.) by regions j
- ➢ Z_j - denotes the amount of added water (water's volume) in location j which are from the activities the local authority or water users implement at the first stage to alleviate the possible water shortage.

Water security level discussion

- The goal function includes the security(risk) factors γ_j

$$F(x,y,z) = \min_{x,y,z} \sum_{i,j,k,m,t} [C_{ij}^{CP} x_{ijmt} + C_{ij}^{CT} x_{ijmt} + C_{ijt}^{CC} x_{ijmt} + C_{ijt}^{CC} x_{ijmt} + C_{kj}^{AP} y_{kjm} + C_{kjm}^{AT} y_{kjm}$$
$$+ C_j^{inv} Z_j] + \sum_{i,j,k,m,t,w} \gamma_j E[\max\{0, W_{ijt} x_{ijmt} + W_{jk} y_{kjm} - W_j(w) - Z_j\}]$$

$$\sum \gamma E[\max\{0, Wx + Wy - W(\omega) - Z\}] \sim \Pr ob[Wx + Wy > W(\omega) + Z]$$

- Optimal condition for $\min F(x,y,z_j)$ is as below:

$$F'_{z_j} = C_j^{inv} - \gamma_j \Pr ob(\sum_{i,k,m,t} (W_{ijt} x_{ijmt} + W_{jk} y_{kjm}) \geq W_j(w) + Z_j) = 0$$

$$\Pr ob(\sum_{i,k,m,t} (W_{ijt} x_{ijmt} + W_{jk} y_{kjm}) \geq W_j(w) - Z_j) = C_j^{inv} / \gamma_j$$ - security level

- ✓ On the left - the probability of water shortage in the location
- ✓ On the right - the ratio of water investment per addition unit of water to the cost/loss associated with water shortage.

- ✓ The robust solution x^*_{ijmt}, y^*_{kjm} from the stochastic model ensures the required water security level C_j^{inv} / γ_j (e.g. water shortage can occur only once in 100 years) .