19th International European Forum (IGLS-Forum) (191st EAAE Seminar)
"Systemic Dynamics and Innovation in Food Networks"

Modeling and managing systemic risk and food - water - energy security nexus in interdependent systems

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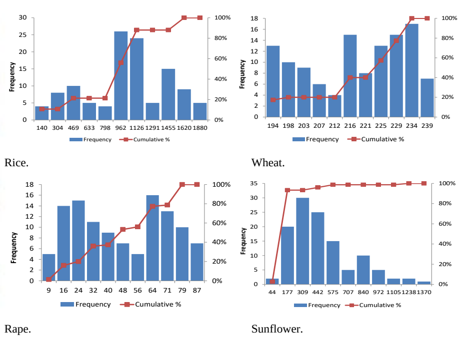
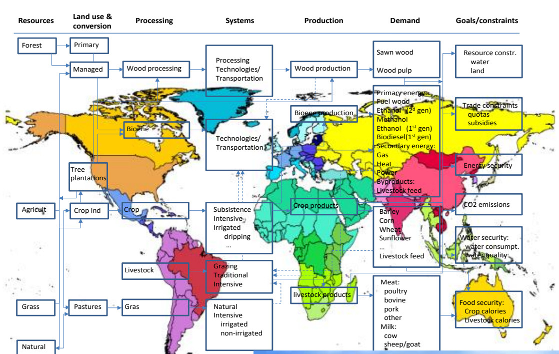
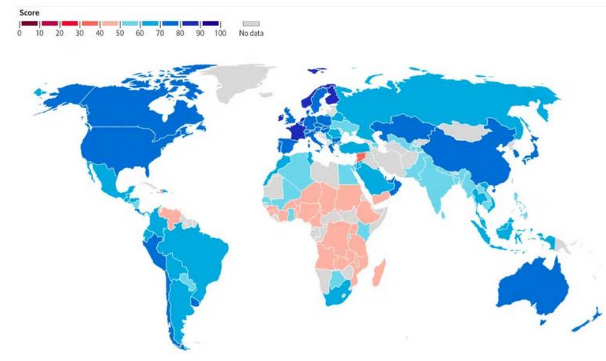
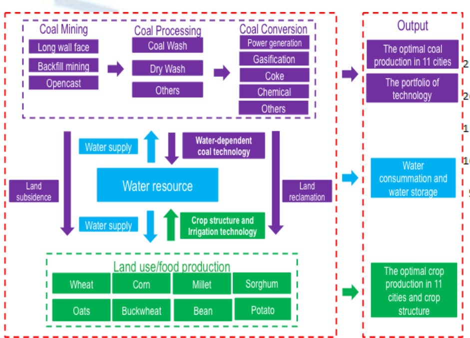
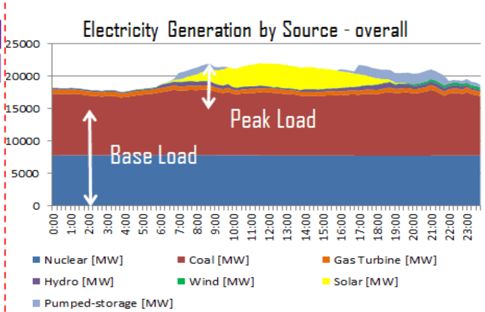


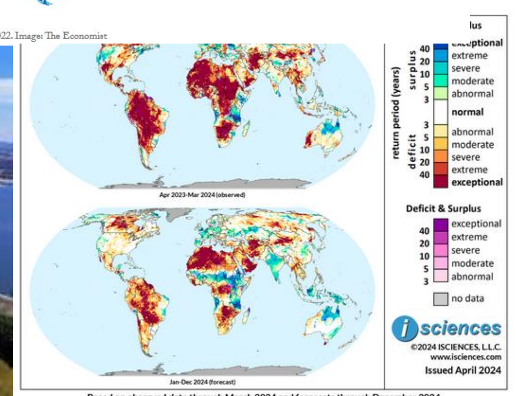




Global Food Security Index 2022. Image: The Economist







Food-Energy-Water-Environmental Nexus

How to deliver water, energy and food for all in a sustainable, safe, secure and equitable way, at affordable prices, adequate quality, preserving the environment and natural ecosystems ?

The Nexus approach moves beyond traditional sectoral (independent) thinking and modeling in order to achieve overall (demand/supply) security and safe/sustainable utilization of all resources:

Water <-> Energy: Water plays a key role in energy production, e.g., in hydroelectric plants, for cooling thermal (fossil-fuel or nuclear) plants and in growing plants for biofuels. Conversely, energy is required to process and distribute water, to treat wastewater, to pump groundwater and to desalinate seawater.

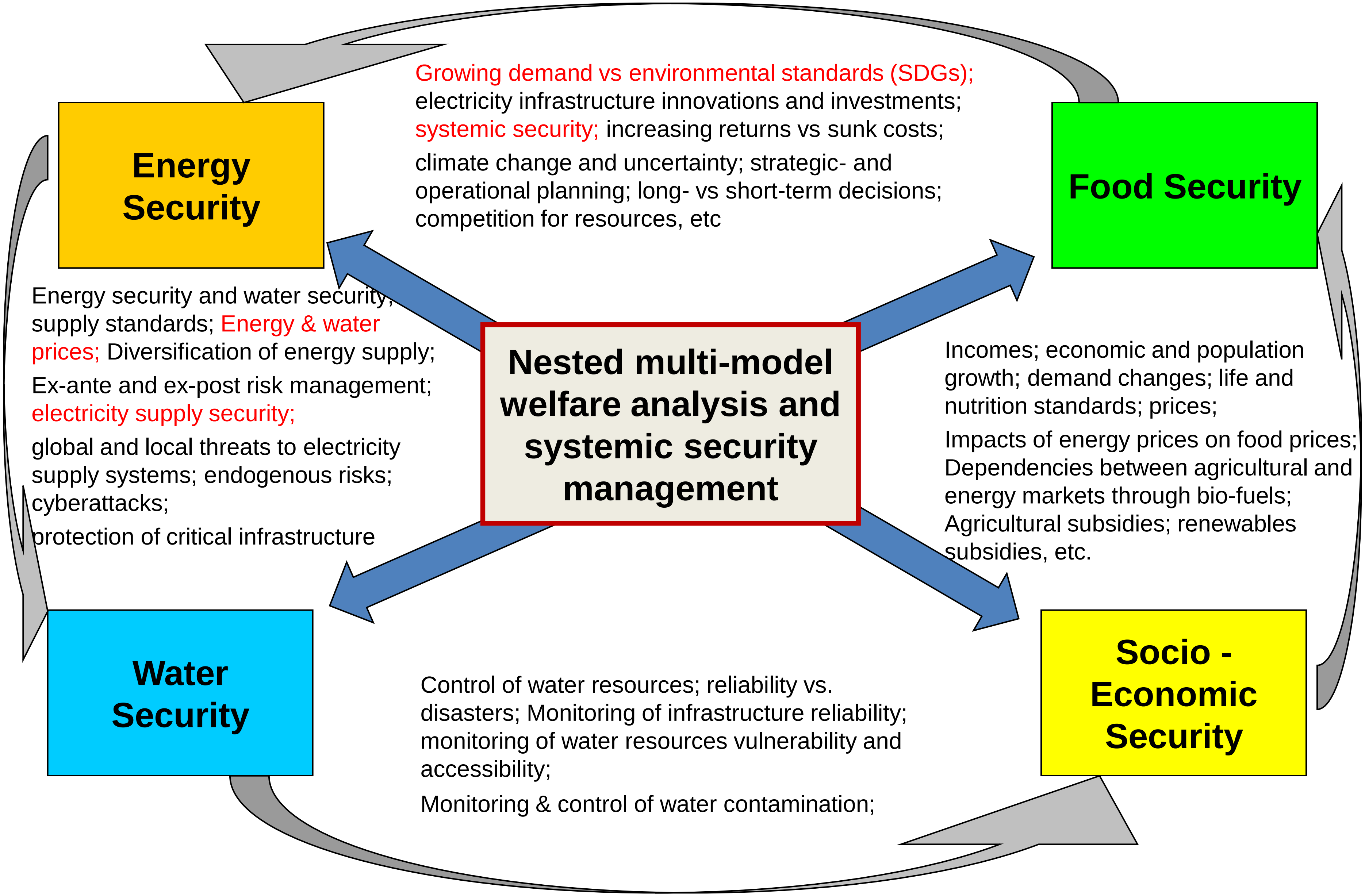
Water <-> Food: Water is the key resource for the entire agro-food supply chain. Conversely, agricultural intensification can affect water quality through nutrients (nitrogen, phosphorus) pollution.

Food <-> Energy: Conflicts around resource use (land and water) for food production may arise in the case of biofuels or extended solar and wind installations.
Energy is an essential input throughout the entire agro-food supply chain, from pumping water to processing, transporting and refrigerating food.

Energy <->Industrial developments: Energy is an essential factor of production, heavy industry, economic developments.

Healthy environment and ecosystems are an essential requirement for the sustainability.

Advanced Analysis of Systemic Depedencies, Risks and Systemic Security



Food, water, energy, ... security nexus

The food, water, energy security nexus according to the Food and Agriculture Organization (FAO) of the United Nations, means that food security, water security, energy security (FEW) are very much linked to one another, meaning that the actions in any one particular FEW sector can have effects in one or both of the other sectors.

The FEWE nexus security approach is necessary to design future, inherently interlinked systems from the starting point **accounting for uncertainty, (systemic) risks, security consideration (constraints)**.

This approach identifies the future systems as inherently interconnected.

The nexus approach aims to highlight potential synergies and identify critical conflicts to be dealt with

Systemic risks can be due to imbalances and inadequate supply-demand-storage relationships triggered by exogenous and endogenous decision-dependent shocks

(Systemic) dependent risks can be analytically intractable, rare and heavy-tailed extreme risks

Food, water, energy security

- Food security is defined by the Food and Agriculture Organization (FAO) as "availability and access to sufficient, safe and nutritious food to meet the dietary needs and food preferences for an active and healthy life".

- Water security has been defined as "the reliable availability of an acceptable quantity and quality of water for health, livelihoods and production, coupled with an acceptable level of water-related risks".

- Energy security has been defined as "access to clean, reliable and affordable energy services for cooking and heating, lighting, communications and productive uses" (United Nations), and as "uninterrupted physical availability [of energy] at a price which is affordable, while respecting environment concerns".

The emphasis on **safeness, reliability, acceptable risks, availability and access** in these definitions implies that **security encompasses variability and extreme situations** such as extreme precipitation, droughts, price shocks, **"disequilibrium"**, norms and quality, at acceptable prices for all including the most vulnerable poor.

Therefore, the **joint security in the FEWE systems is understood as an ability to fulfill the norms and needs of the society for food, energy, water, provision of social benefits, environmental conditions, etc.,** in all **circumstances/scenarios** under requirements for prices, qualities, quantities, and accounting for inherent risks.

Systemic Risks

Systemic risks in interdependent Food-Energy-Water-Environmental (FEWE) systems can be defined as the risks of a subsystem (a part of the system) threatening the sustainable performance and achievement of FEWE security goals.

Thus, a shock in a peripheral subsystem induced (intentionally or unintentionally) by an endogenous or exogenous event, can trigger systemic risks propagation with impacts, i.e., instability or even a collapse, at various levels.

The risks may have quite different policy-driven dependent spatial and temporal patterns.

Systemic risks emerge due to systemic imbalances, i.e., shortfalls in supply-demand relationship.

Systemic (cascading) risks in FEWE systems are implicitly defined by the whole structure and the (supply-demand-storage) balances among the systems, costs, prices, technologies, trade, risk exposures and risk measures, (FEWE) security/safety norms and constraints, decisions of agents.

Systemic Risks: Examples

In energy systems, extra load in a power grid triggered by a power plant, variable energy resources, or a transmission line failure can cause cascading failures with catastrophic systemic outages [1].

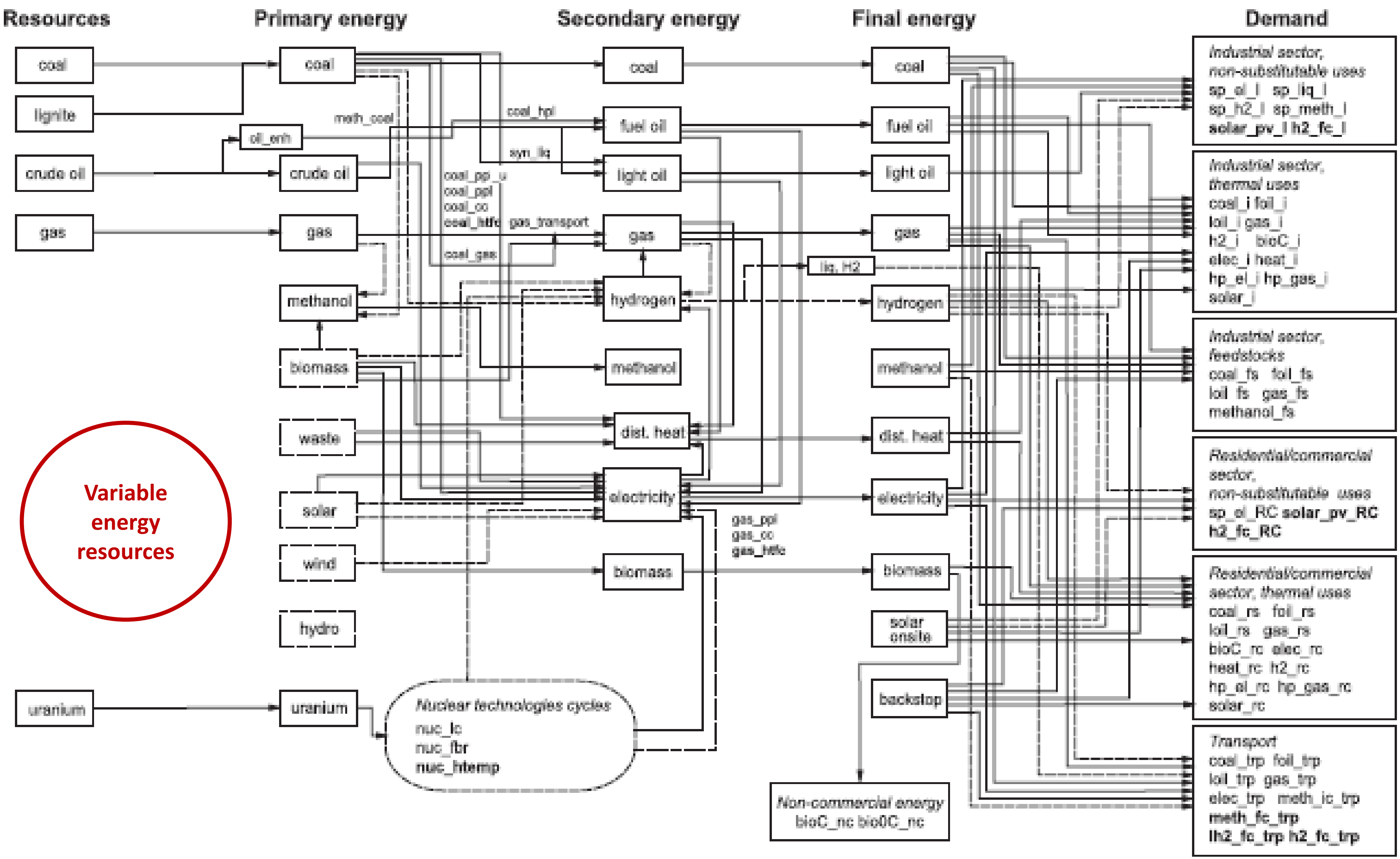
In financial networks, an event at a company level can lead to severe instability or even to a crisis similar to the global financial crisis 2008.

In land use management, a hurricane in combination with inappropriate dams' maintenance and land use management can result in human and economic losses, similar to those induced by Hurricane Katrina [2].

In infrastructure systems, inappropriate buildings' codes can trigger extreme structural, economic, human losses (2023 Turkey-Syria Earthquake)

In water supply systems, lack of water supply in 2024 California fires: "… losing supplies from fire hydrants likely impaired the effort to protect some homes and evacuation corridors…." (Time J., 2024) (https://time.com/7206352/los-angeles-firefighters-water-supply-access-complaints-investigation/)

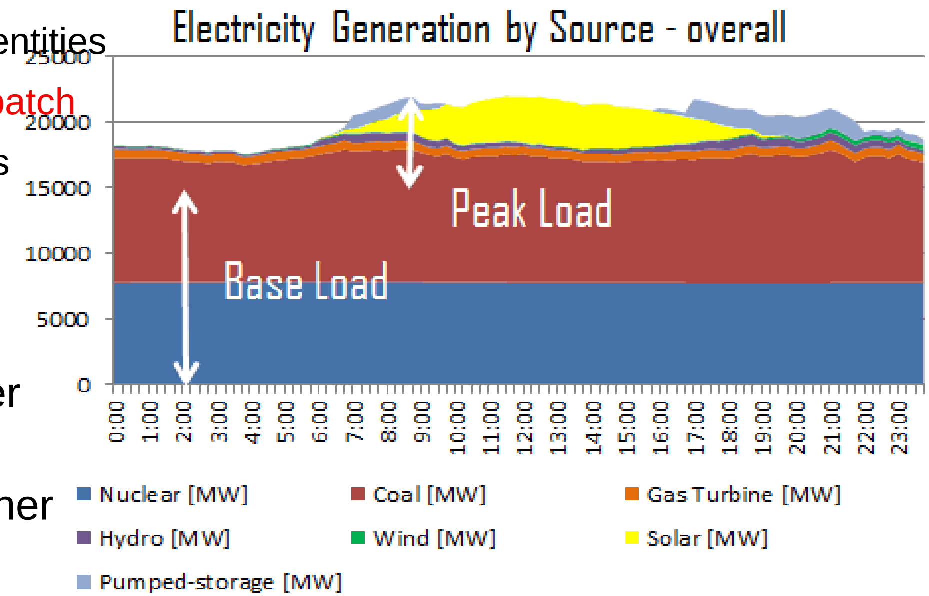
Energy production and demand structure: interdependencies, uncertainties and systemic risks



Schematic diagram of the energy model MESSAGE. Source: Nakicenovic et al., 2002; Ermoliev et al. 2010, etc.

Model-based planning

- Emerging risks – deregulation, decentralization, variable resources
  - Multiple energy/electricity generation companies/entities
  - Requires strict regulation of energy/electricity dispatch
  - Systemic risks and vulnerability of energy markets
  - Transboundary issues and energy balancing
  - Optimal dispatch and pick prices
- Stochastic threats from wind, solar, hydropower
- Stochastic supply vs demand depend on weather
- Short- and long-term energy systems planning
  - Uncertainties of climate change
  - Systemic uncertainties and risks due to new technologies
  - Technological uncertainties, future electricity consumption, e.g. electric cars, etc.
  - Scarcity of resources, e.g. water scarcity
  - Methodological risks, application of inadequate model/method
  - Stakeholder involvement and model-based dialogue
  - Changing risk perception via a model
  - Rare natural resources requirements (in EU?)
  - Ignorance of risks



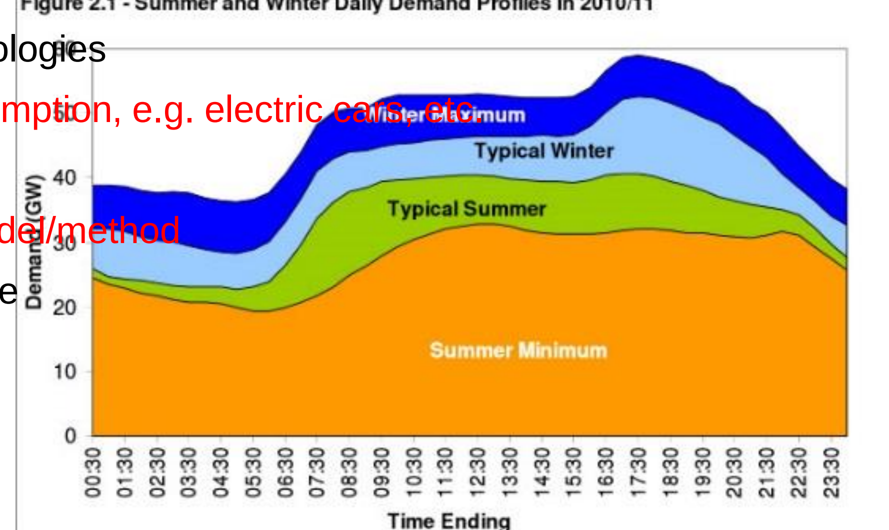
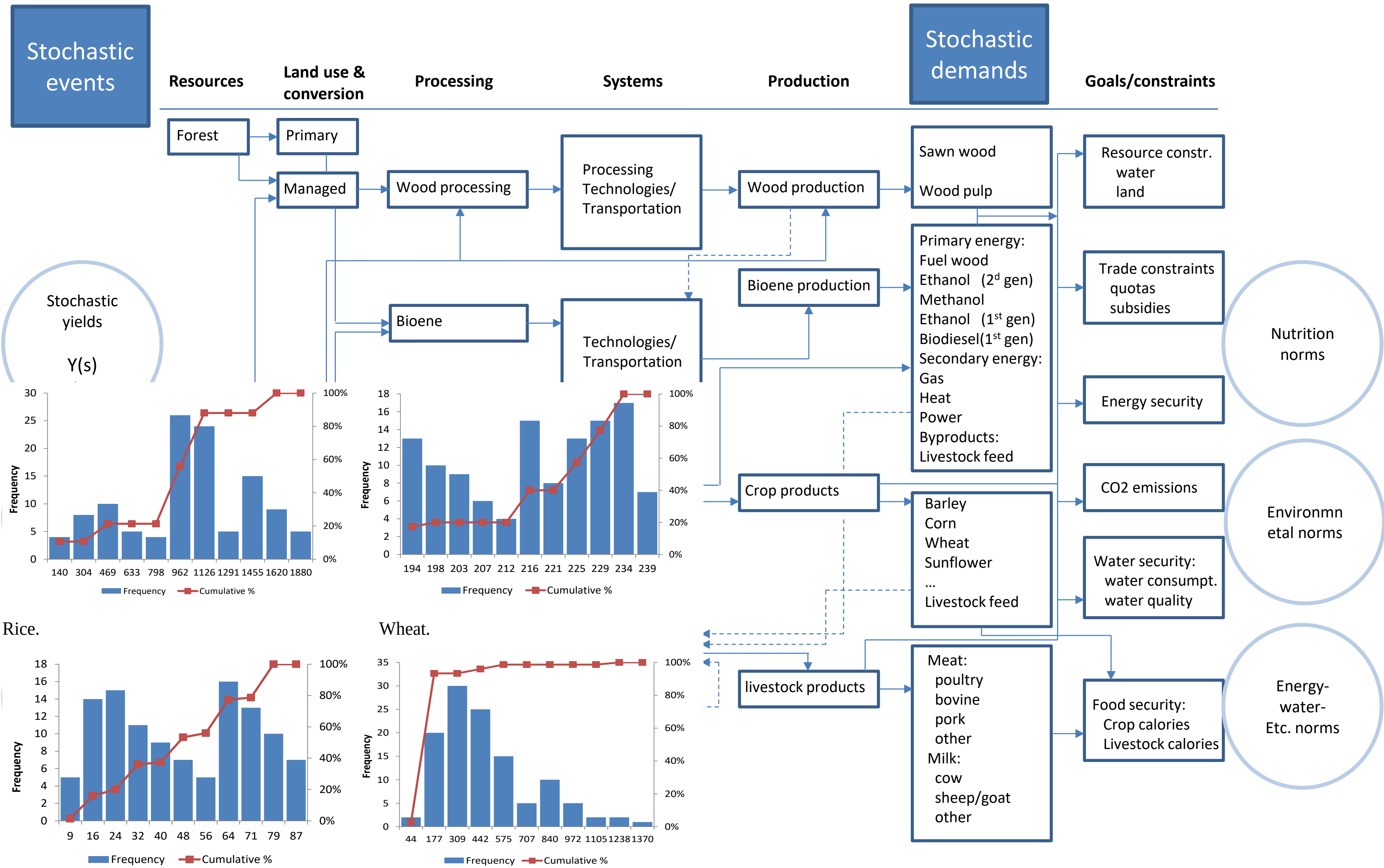


Figure 2.1 - Summer and Winter Daily Demand Profiles in 2010/11

Systemic interdependencies in land use systems



Rice.

Wheat.

Rape.

Sunflower.

Stochastic land use model: goal function

Maximize welfare

$$
\begin{aligned}
&\mathrm{E}\left(\begin{aligned}&\sum\left[\int \varphi^{demd}_{r,t,y}\left(D_{r,t,y}(\omega)\right)\mathrm{d}(\cdot)\right]-\sum_{r,\tilde{r},y}\left[\int \varphi^{trad}_{r,\tilde{r},t,y}\left(T_{r,\tilde{r},t,y}(\omega)\right)\mathrm{d}(\cdot)\right]\\
&-\sum_{r}\left(\tau^{live}_{r}\cdot B(\omega)_{r,t}\right)-\sum_{r,m}\left(\tau^{proc}_{r,m}\cdot P_{r,t,m}(\omega)\right)-\sum_{r,e}\left(\tau^{emit}_{t,e}\cdot E_{r,t,e}(\omega)\right)\end{aligned}\right)\\
&-\sum_{r}\left[\int \varphi^{splw}_{r,t}\left(W_{r,t}\right)\mathrm{d}(\cdot)\right]\\
&-\sum_{r,l,\tilde{l}}\left[\int \varphi^{lucc}_{r,l,\tilde{l},t}\left(\sum_{c,o,p,q} X_{r,t,c,o,p,q,l,\tilde{l}}\right)\mathrm{d}(\cdot)\right]\\
&-\sum_{r,c,o,p,q,l,b,m}\left(\tau^{land}_{c,o,p,q,l,b,m}\cdot X_{r,t,c,o,p,q,l,b,m}\right)
\end{aligned}
$$

FEWE Security constraints

Production-demand 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 $P\{D_{r,t,F}<D^{*}_{r,t,F}\}\le p_{r,t,F}$ and

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

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

Challenges

- Deterministic scenario-dependent solutions can be dangerous
- Scenario-by-scenario deterministic analysis is dangerous
- Irreversibility and Maladaptation
- Representation of uncertainty and risks
- Skewed and multimodal distributions
- Nonparametric vs parametric risks modeling
- Modeling of Risk Aversion -> Uncertainty -> Risk -> Reversibility
- Modeling of future flexibility & learning
- Systemic risks
- Two-stage (multi-stage) stochastic optimization
- Price-endogenous stochastic optimization models

Deterministic scenario-dependent vs robust

- (Im)balance: (production) x $= d(\omega)$ (random demand); in what sense

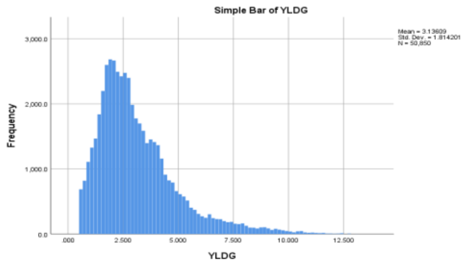
“ $x = d(\omega)$ “

- Can be also: (random production) x (ω) $= d(\omega)$ (random demand)

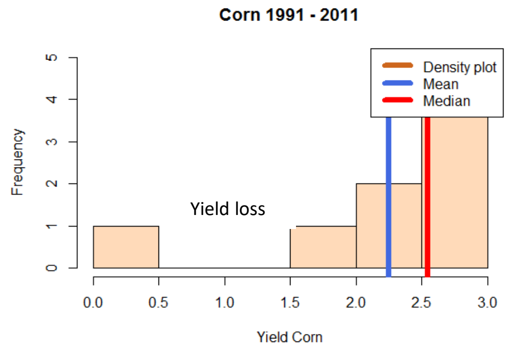
Deterministic

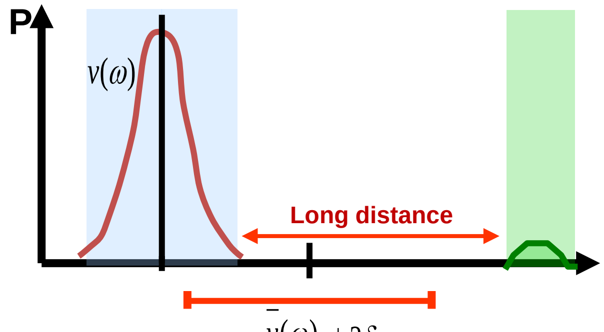
- Deterministic scenario analysis: what is optimal production once demand becomes known (simulated) ?

$$d_1, d_2, d_3, \ldots \quad \Rightarrow \quad x_1^{opt} = d_1, \; x_2^{opt} = d_2, \; x_3^{opt} = d_3, \ldots$$

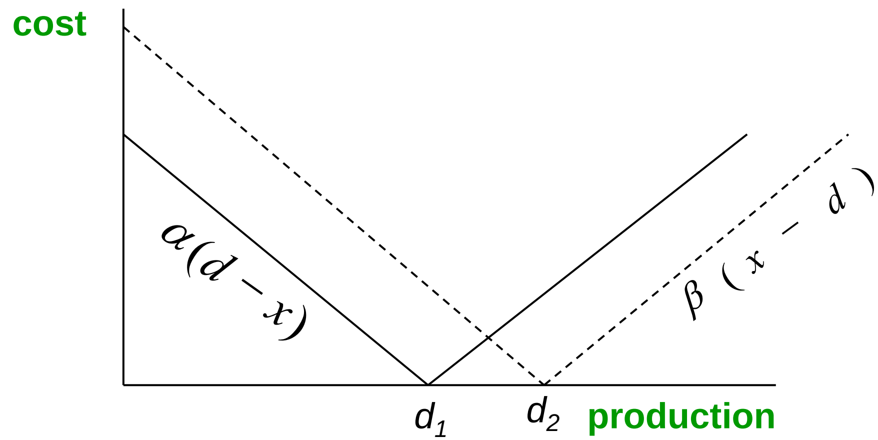


- Deterministic model: (production) x = E $d(\omega)$ (average demand)





Costs associated with systemic imbalances (shortfalls or exceedance), overshooting and undershooting costs



Problem: minimize costs

$$f(x,\theta)=\begin{cases}\alpha(x-d(\omega)), x \ge d(\omega)\\ \beta(d(\omega)-x), x < d(\omega)\end{cases}$$

- ω – are random scenarios $\omega_{1,}\omega_{2,}$ ..., ω_n ,... ω_S .

- Minimax solution: take worst-case scenario max ($d(\omega)$):

This leads to conservative decision x= max($d(\omega)$), i.e. production level to meet the highest demand –

too costly solution !

- **Robust solution: Minimize expected value of a "systemic" cost**

  - $F(x) = E\alpha(d-x)I(d>x) + E\beta(x-d)I(x \geq d) = E\max\{\alpha(d-x), \beta(x-d)\}$

- Anticipative and adaptive two-stage decision:

production ***x*** is selected ex-ante according to the following:

$$P[x \geq d] = \frac{\alpha}{\alpha + \beta}$$ **(VaR)** ***F(x^rob^)* = CVaR**

optimal production ***x*** is a quantile of *d* defined by costs α , β and the prob. distribution of *d*

Production planning and systemic risk sharing

Deterministic, not accounting for risks: Two producers/regions/feedstocks (corn, wheat) P1 and P2 with production costs: $c_1 < c_2 < b$; d – demand for bioethanol:

minimize $c_1 x_1 + c_2 x_2$

$$a_1 x_1 + a_2 x_2 \geq d \quad x_1 \geq 0 \quad x_2 \geq 0$$

solution $x_1^* = d \quad x_2^* = 0$

Stochastic, accounting for risks: a_1 and a_2 are random shocks/(yields) to production

minimize $c_1 x_1 + c_2 x_2$

$$a_1(\omega_s) x_1 + a_2(\omega_s) x_2 \overset{?}{\geq} d$$

Emergency of systemic risks and risk sharing

Instead, we require the safety constraint that

$$Prob[a_1 x_1 + a_2 x_2 \leq D] \leq p$$

minimize $F(x) = c_1 x_1 + c_2 x_2 + \mu E \max\{0, D - a_1(\omega)x_1 - a_2(\omega)x_2\}$

where $\mu E \max\{0, D - a_1(\omega)x_1 - a_2(\omega)x_2\}$ is the expected storage/import cost if demand exceeds the supply

New system with trade or/and storages!

Land decisions x are strategic and scenario-specific trade or storage are adaptive

μ can be chosen to satisfy the safety constraint with required probability, $0 \leq p \leq 1$, i.e. for a percentage (percentile) of scenarios.

Emergency of systemic risks and risk sharing

Example:

If only efficient producer (P1, *c1 < c2 < b*) **is at risk:** $0 < \mathrm{E}\, a_1 < 1,\ a_2 = 1$.

Market share of the P2 (risk-free producer with higher production costs):

Take derivative $$F_{x_2}(x_1, x_2) = c_2 - \mu P[D > a_1 x_1 + x_2]$$

Optimal land area (share) $x_2^* > 0$ of risk-free **P2** is defined by the quantile

$P[D > a_1 x_1^* + x_2^*] = c_2 / \mu$ of the distribution function describing

contingencies of the risky **P1**, i.e., a_1 , and the ratio c_2 / μ.

Main challengies

- **Modeling of systemic risks**
  - Propagation of risks, multivariate multisystem multiagent spatially and temporary dependent risks
  - Risks are „shared“, often - magnified by interdependencies, constraints, targets
  - Catastrophic losses may be caused by peripheral event
- **Introduction of risk aversion through 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
- **Robust decisions (RD) instead of „exact“ prediction**
  - Robust decisions leave us better-off independently of what uncertainty scenario realises
- **RDs lead to systems analysis (SA) instead of analysis of existing systems**
  - Improvement of systems to tackle the problems
  - Inclusion of new nonexisting technologies, financial instruments, crops portfolios
  - Design of new systems
- **Quantile-based instead of average indicators, probabilistic constraints, VaR and CVaR constraints risk measures and constraints**
- **Mutli-stage (two-stage) decisionmaking – anticipation and adaptation**
- **Practical application: Design of unified robust policies, e.g., for CAP, Emissions trading, multipurpose reservoir operation**

Traditional Approaches

- **Disintegrated analysis of systems (e.g. food-water-energy-environment) is dangerous**
  - Example: Estimation of (biofuels) agricultural production without accounting for:
    - other systems‘ constraints and demands for natural resources, e.g. water, land (current studies of energy security in China)
    - biofuels introduced competition for resources
    - biofuels targets are tight (especially under weather variability and climate uncertainties)
    - Biofules dependence of agricultural markets on crude oil markets

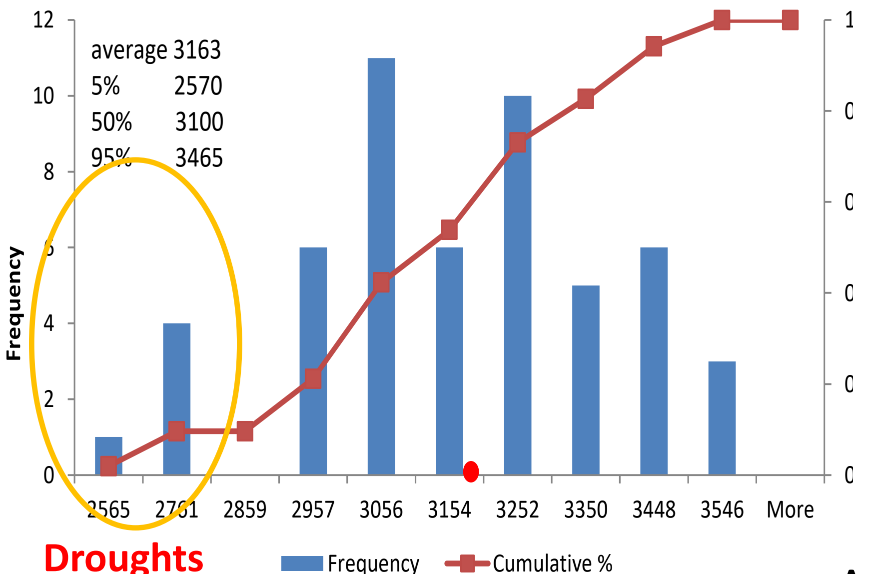
- **Certainty about systems and agents**
  - Deterministic scenario-by scenario e.g. input-output-based analysis (popular in crosssectoral planning)
  - Life-cycle analysis (used, e.g., for bioenergy analysis)

- **Deterministic (average) models – no long-term planning strategic decisions**
  - Distinguishes only one type of decisions (strategic). Does not evaluate short-term
  - 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

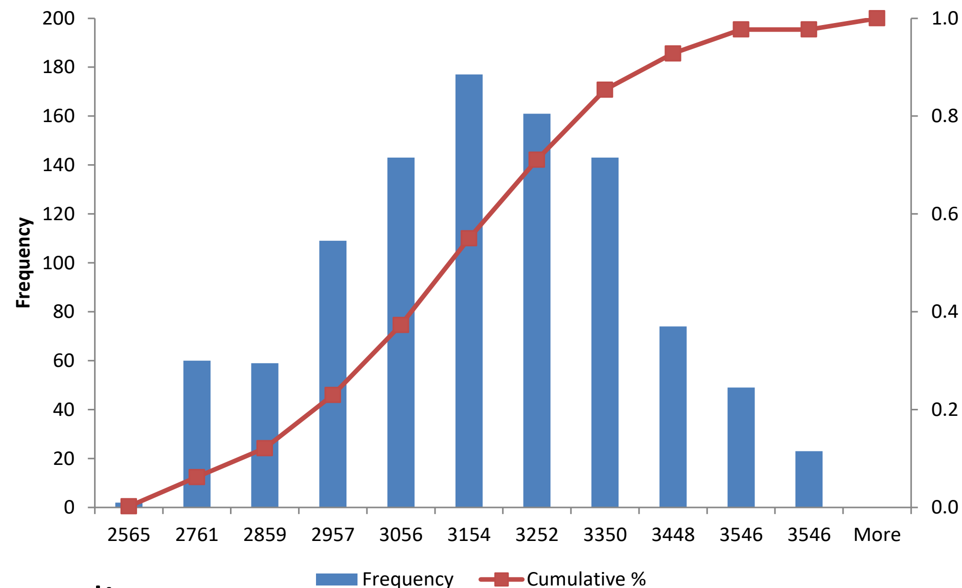
- **Not addressing interdependent systemic risks**
  - Independent risks (e.g. insurance models)
  - Traditional models use average indicators
    - The law of large numbers does not work – pooling of dependent risks increases insecurity
    - Actuarial „average“-based risk-pricing models are wrong
    - NPV - discounting rate equals average market return, has to depend on the events probability

- **The need for quantile-based instead of average indicators**
  a. 100 assets can be lost with probability 1/100
  b. Each individual asset can be lost with probabillity 1/100. Probability to loose all assests 100^{-100}
  c. **Average loss is the same == 1 !**

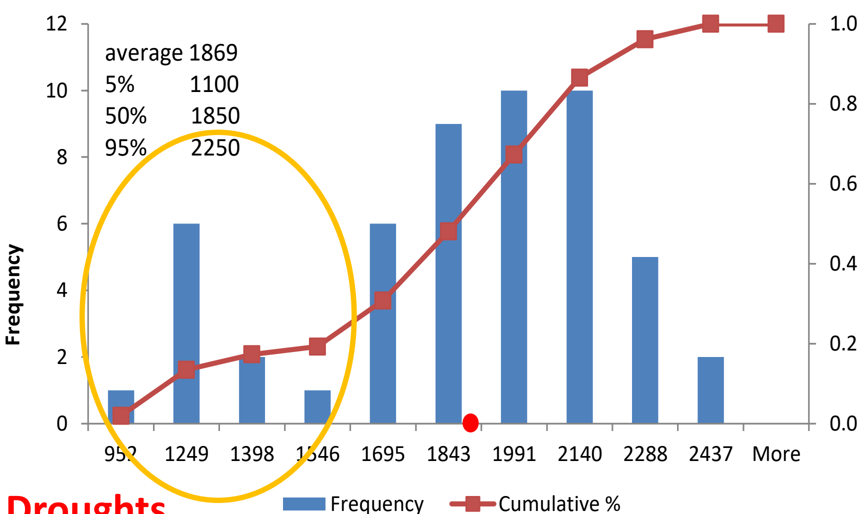
- Most important is to represent the quantile (extreme values) of indicators and their trends (e.g., for different RCP scenarios)



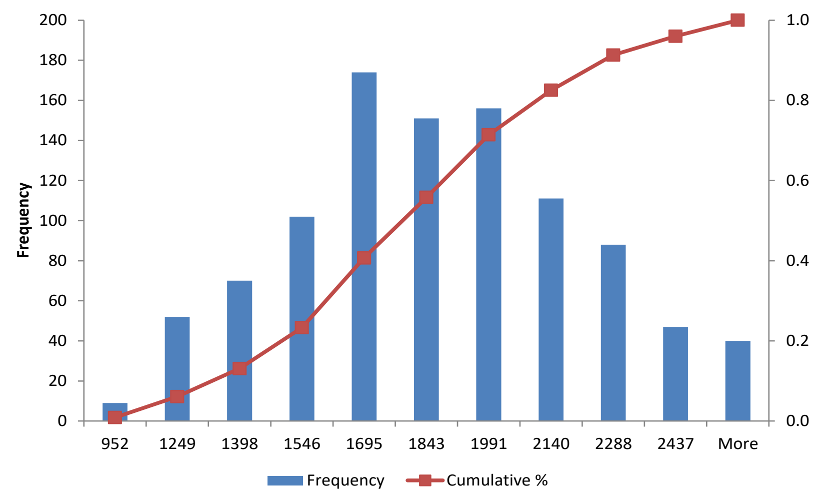
Droughts

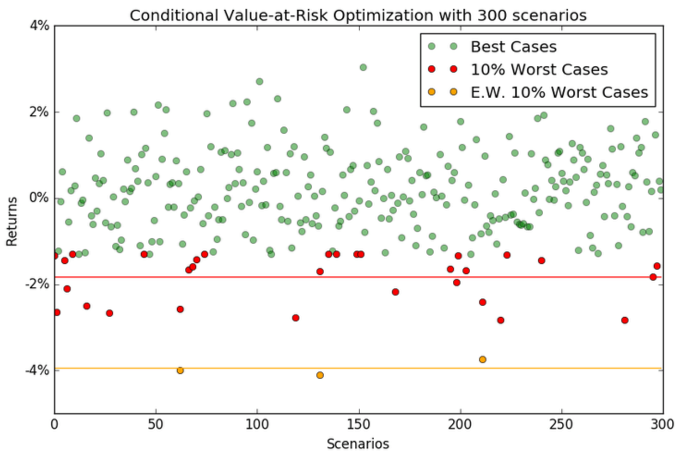


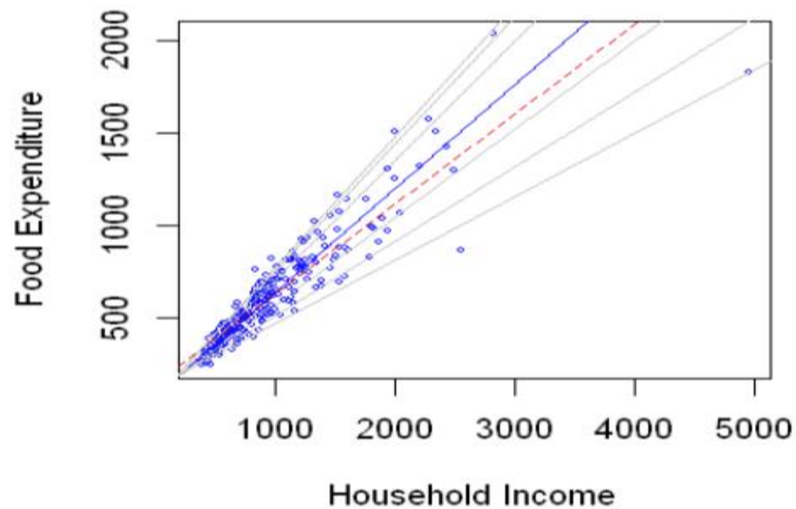
Australia

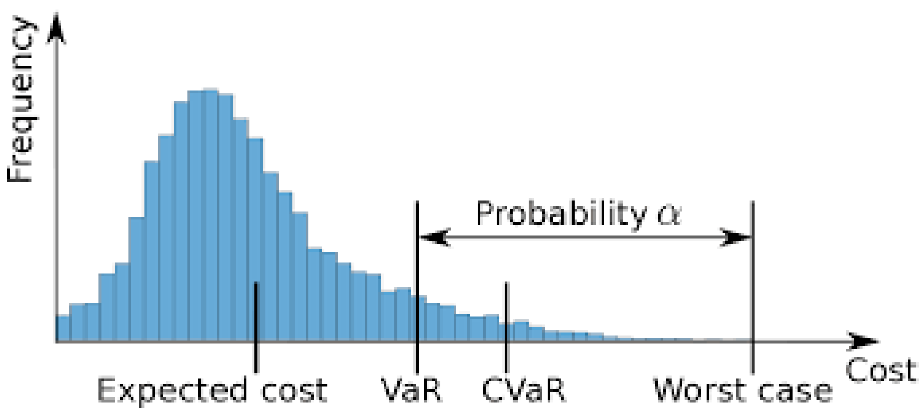


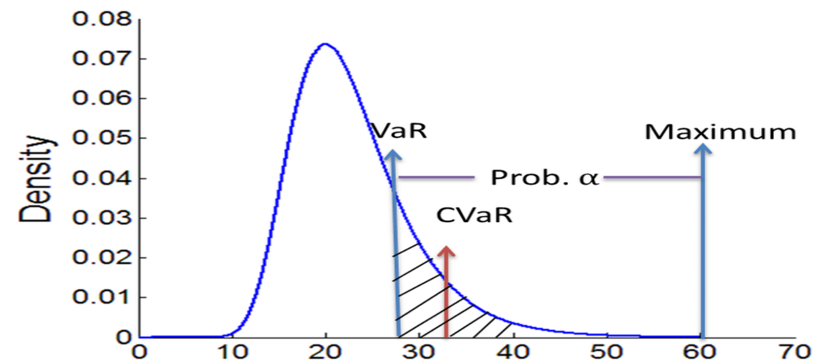
Droughts

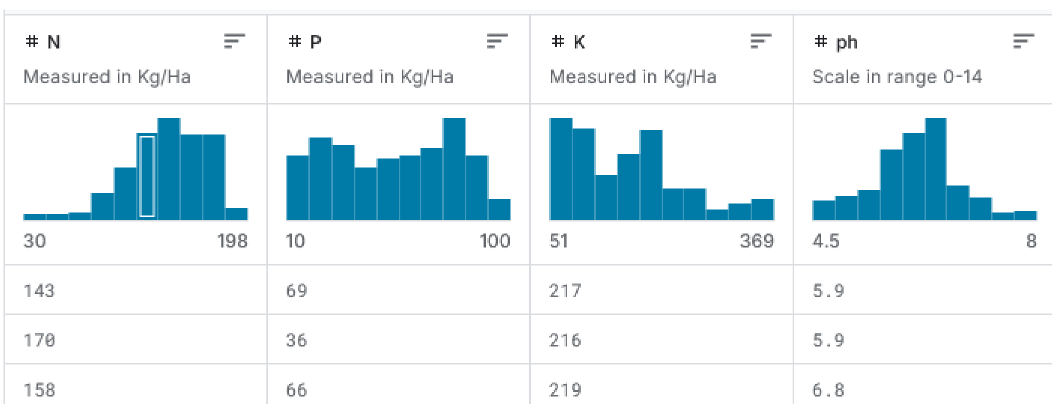




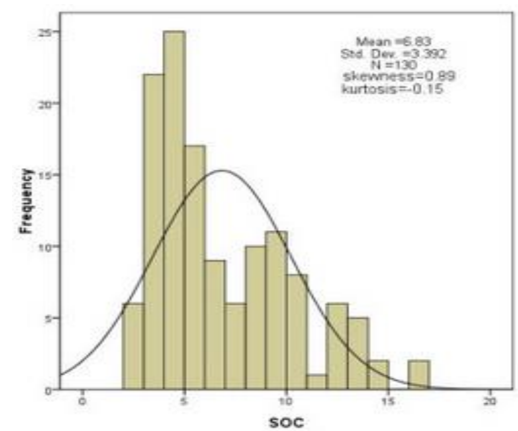




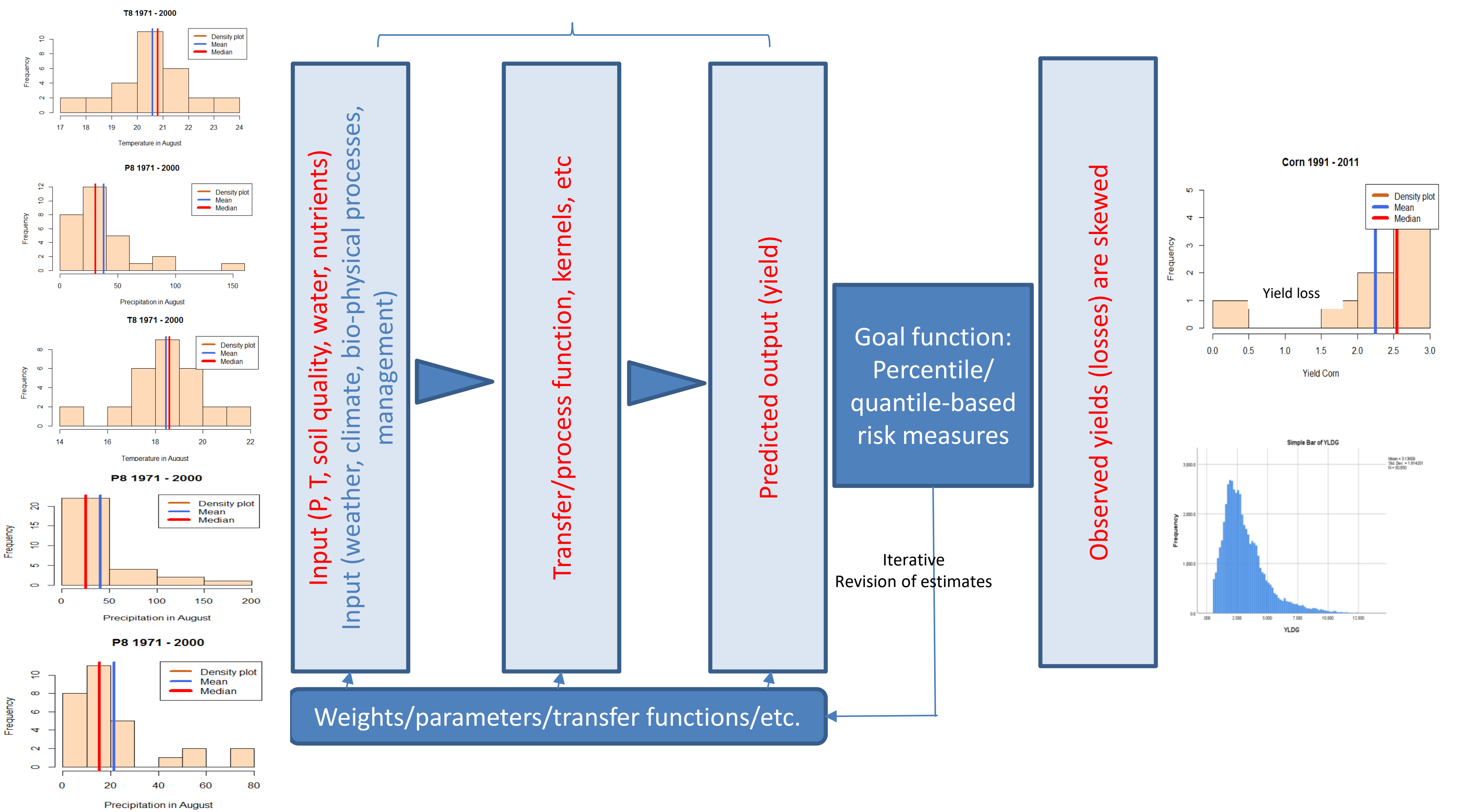




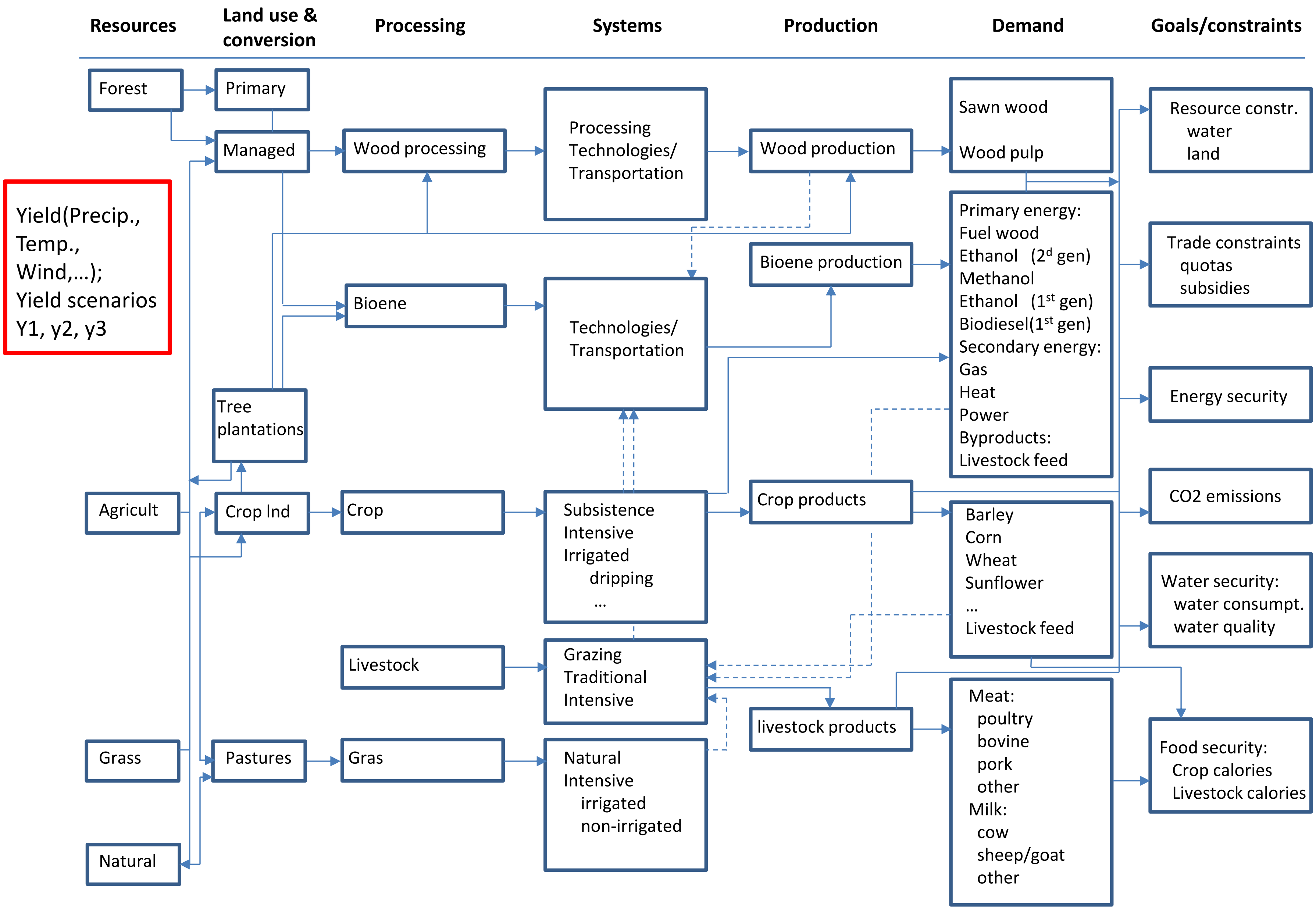
# N	# P	# K	# ph
Measured in Kg/Ha	Measured in Kg/Ha	Measured in Kg/Ha	Scale in range 0-14
30 198	10 100	51 369	4.5 8
143	69	217	5.9
170	36	216	5.9
158	66	219	6.8



Example of ML and ANN:
Stochastic generator of crop yields based on GIS data of
T, P, SPEI, soil, water, EPIC data, Monthly, 1km2 resolution, RCPs



Systemic interdependencies in land use systems



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29.05.2023

Connections between Robust Statistical Es[...] Robust Decision-Making with Two-Stage [...] Optimization, and Robust Machine Learni[...] Problems

verfasst von: T. Ermolieva, Y. Ermoliev, P. Havlik, A. Lessa-Derci-Augustynczik, N. Komendan[...]

A Novel Robust Meta-Model Framework f[...] Predicting Crop Yield Probability Distribut[...] Multisource Data

Authors: T. Ermolieva, P. Havlík, A. Lessa-Derci-Augustynczik, E. Boere, S. Frank, T. Kahil, G. Skalský, C. Folberth, N. Komendantova, P. S. Knopov

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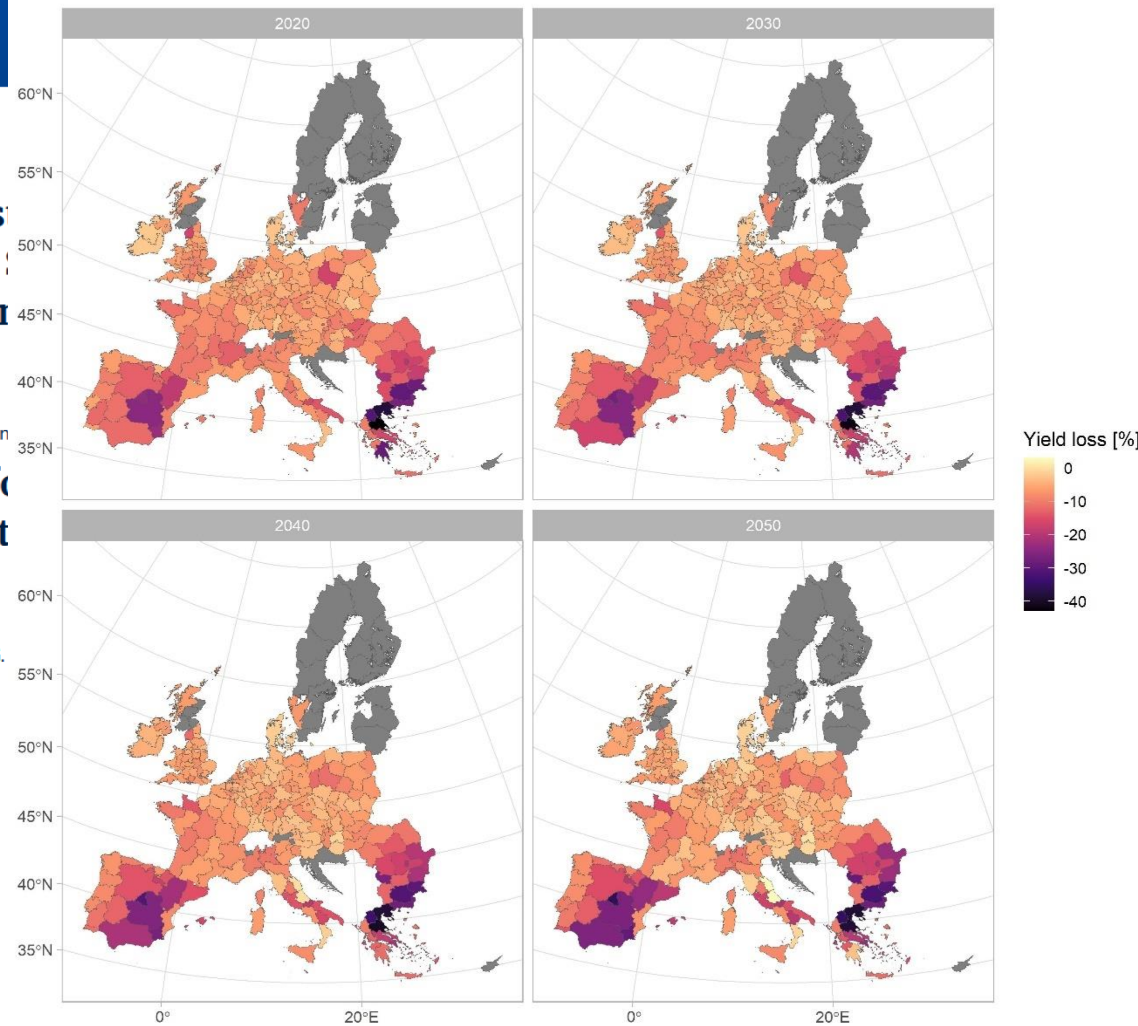


Crop yield loss as the difference between the 75th and the average crop yield, from 2000 to 2050, in percentage terms, for rainfed maize, RCP26

Stochastic land use model: goal function

Maximize welfare

$$
\begin{aligned}
&\mathrm{E}\left(\begin{aligned}&\sum\left[\int \varphi^{demd}_{r,t,y}\left(D_{r,t,y}(\omega)\right)\mathrm{d}(\cdot)\right]-\sum_{r,\tilde{r},y}\left[\int \varphi^{trad}_{r,\tilde{r},t,y}\left(T_{r,\tilde{r},t,y}(\omega)\right)\mathrm{d}(\cdot)\right]\\&-\sum_{r}\left(\tau^{live}_{r}\cdot B(\omega)_{r,t}\right)-\sum_{r,m}\left(\tau^{proc}_{r,m}\cdot P_{r,t,m}(\omega)\right)-\sum_{r,e}\left(\tau^{emit}_{t,e}\cdot E_{r,t,e}(\omega)\right)\end{aligned}\right)\\
&-\sum_{r}\left[\int \varphi^{splw}_{r,t}\left(W_{r,t}\right)\mathrm{d}(\cdot)\right]\\
&-\sum_{r,l,\tilde{l}}\left[\int \varphi^{lucc}_{r,l,\tilde{l},t}\left(\sum_{c,o,p,q} X_{r,t,c,o,p,q,l,\tilde{l}}\right)\mathrm{d}(\cdot)\right]\\
&-\sum_{r,c,o,p,q,l,b,m}\left(\tau^{land}_{c,o,p,q,l,b,m}\cdot X_{r,t,c,o,p,q,l,b,m}\right)
\end{aligned}
$$

FEWE Security constraints

Production-demand 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

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

Environment security

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

(Bio) energy security

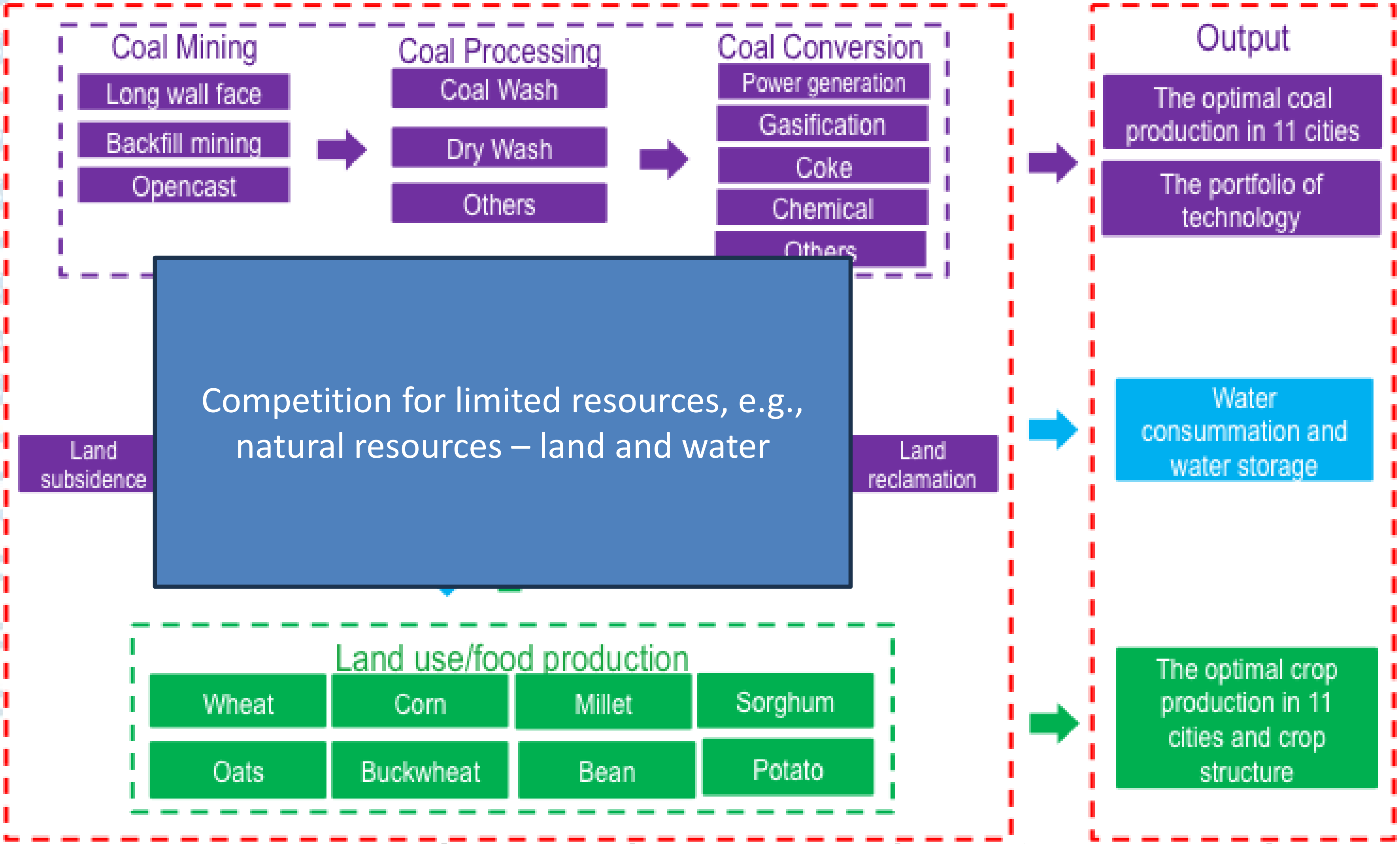
$$P\{D_{r,t,Be}<D^{*}_{r,t,E}\}\le p_{r,t,Be}$$

maximize $$F(x) = EProfit(x,\omega) + \mu E \min\{0, D - D^*)\}$$

Robust percentile-based stochastic GLOBIOM:

- Contributes to the design and evaluation of robust CAP policies:
  - Diversifies systemic risks through trade to avoid price and demand shocks;
    - New shock does require significant adjustments
  - Buffers global and local shocks through robust storages;
  - Avoids costly (irreversible) investments into infrastructure (irrigation)
- Increases demand and fulfils food security at lower prices
- Evaluates the requirement in new technologies: irrigation, processing, etc.
- Evaluates the need in financial instruments: subsidies, taxes, investments, insurance, credits, …
- Addresses modelling, sharing (transferring) and pricing of “interdependent” systemic risks

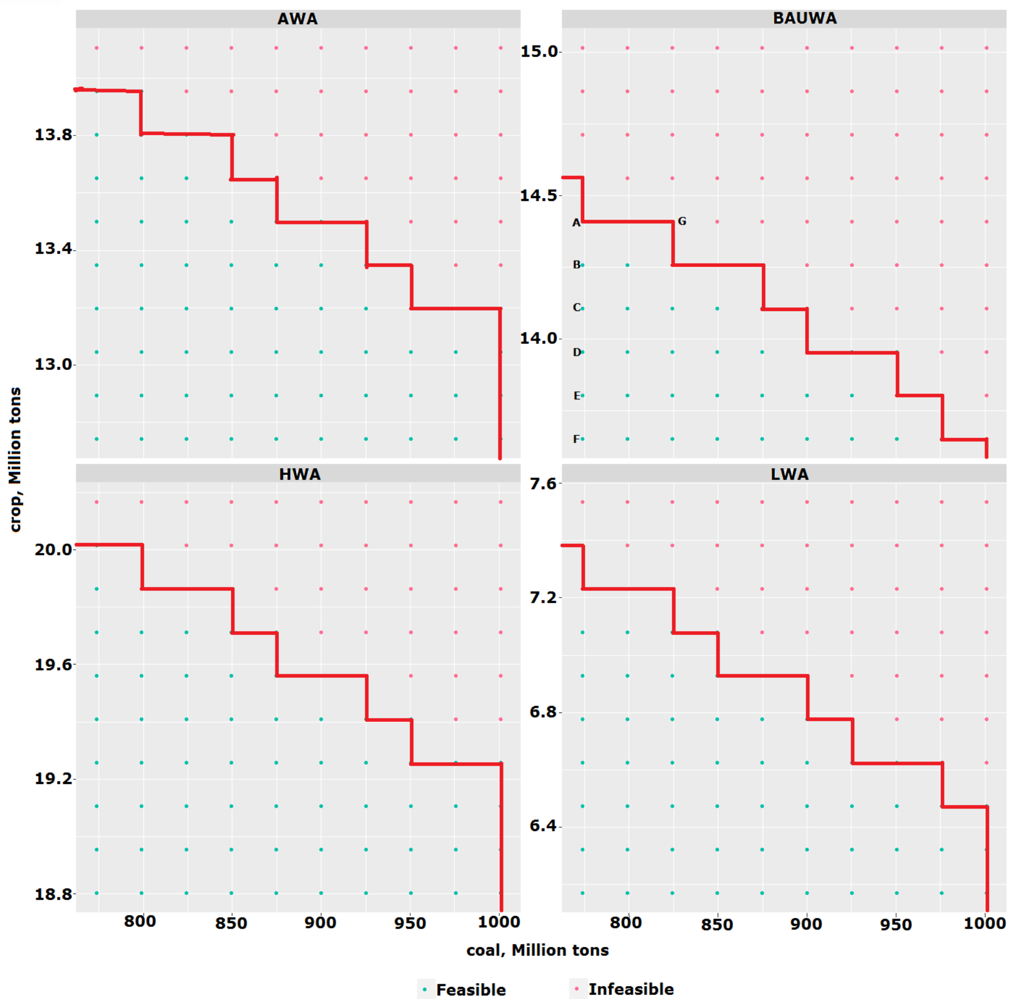
Example of Energy-Water-Food-Environmental NEXUS



Competition for limited resources, e.g., natural resources – land and water

Gao, J., Xu, X., Cao, G.-Y., Ermoliev, Y., Ermolieva, T., & Rovenskaya, E. (2021). *Strategic decision-support modeling for robust management of the food–energy–water nexus under uncertainty.* Journal of Cleaner Production 292 e125995. 10.1016/j.jclepro.2021.125995

Feasibility analysis of coal vs crop production under alternative water availability constraints



Production-Possibility frontier of the coal and agriculture production under different water availability constraints.

"BAUWA", "AWA", "HWA", "LWA" are four different water availability scenarios.

X-axis is the alternative demands of coal; Y-axis is the alternative demands of crop.

Each scenario has 100 points; each point means one alternative demand combination of crop and coal.

The feasible points in the respective water constraint scenario are marked by blue points.

Distributed systems linkage with iterative "learning" procedure

Model of sector/region A

Minimizing costs

$$\langle c_A, x_A \rangle \to \min_{x_A}$$

Constraints on volume of production

$$R_A x_A \le \rho_A$$

$$M_A x_A \le y_A$$

$$x_A \ge 0$$

Constraints on available resources (land, water, etc.)

☹ $$D_A y_A \le d_A$$

Model of sector/region E

$$\langle c_E, x_E \rangle \to \min_{x_A}$$

$$R_E x_E \le \rho_E$$

$$M_E x_E \le y_E$$

$$x_E \ge 0$$

$$D_E y_E \le d_E$$ ☹

Can be separated for simplicity but in reality are inter-linked!

$$D_A y_A + D_E y_E \le d$$

☺ ☺ ☺

"Naïve" approach: direct iterative exchange between models

$$\langle c_A, x_A \rangle \rightarrow \min_{x_A}$$
$$R_A x_A \le \rho_A$$
$$M_A x_A \le y_A$$
$$x_A \ge 0$$

$x_A(k+1), y_A(k+1)$

$x_E(k), y_E(k)$

$$\langle c_E, x_E \rangle \rightarrow \min_{x_A}$$
$$R_E x_E \le \rho_E$$
$$M_E x_E \le y_E$$
$$x_E \ge 0$$

$D_A y_A + D_E y_E(k+1) \le d$

$y_E(k)$

$y_A(k)$

$D_A y_A(k) + D_E y_E \le d$

$$D_A y_A + D_E y_E \le d$$

“Naïve” approach: example – dependence on the initial condition!

$$\langle c_A, x_A \rangle \to \min_{x_A}$$
$$R_A x_A \le \rho_A$$
$$M_A x_A \le y_A$$
$$x_A \ge 0$$

$$\langle c_E, x_E \rangle \to \min_{x_A}$$
$$R_E x_E \le \rho_E$$
$$M_E x_E \le y_E$$
$$x_E \ge 0$$

$$D_A y_A + D_E y_E \le d$$

Linking models via a central "hub" under uncertainty and asymmetric information

$$y(0)=(y_A(0),y_E(0)):\quad D_A y_A(0)+D_E y_E(0)\le d$$

$$\langle u_A,\rho_A\rangle+\langle \upsilon_A, y_A(k)\rangle \to \min_{u_A,\upsilon_A}$$
$$R_A u_A + M_A \upsilon_A \ge c_A$$
$$u_A\ge 0, \upsilon_A \ge 0$$

$$\langle u_E,\rho_E\rangle+\langle \upsilon_E, y_E(k)\rangle \to \min_{u_E,\upsilon_E}$$
$$R_E u_E + M_E \upsilon_E \ge c_E$$
$$u_E\ge 0, \upsilon_E \ge 0$$

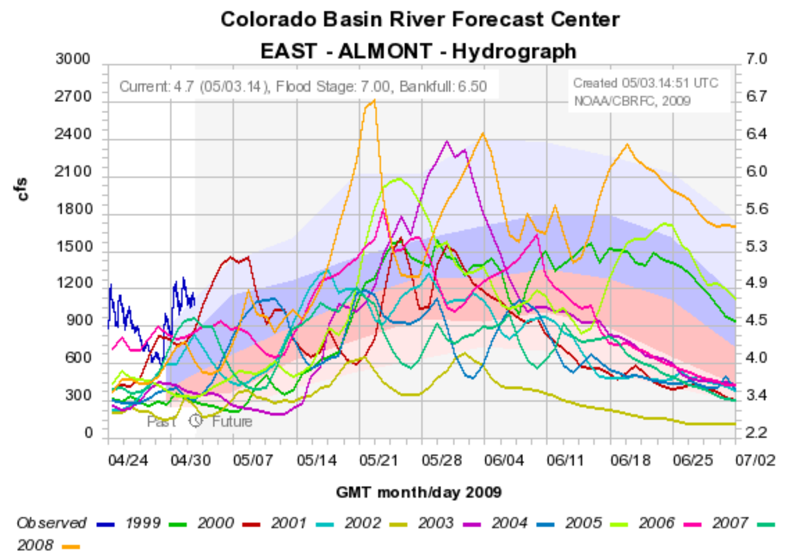
Ermolieva, T., Ermoliev, Y., Zagorodny, A., Bogdanov, V., Borodina, O., Havlik, P., Komendantova, N., Knopov, P., et al. (2022). Artificial Intelligence, Machine Learning, and Intelligent Decision Support Systems: Iterative "Learning" SQG-based procedures for Distributed Models' Linkage. *Artificial Intelligence Journal*, 94 (2), 10.15407/jai2022.02.092.

$$y_A(k+1)=\pi_Y(y_A(k)+\alpha(k)\upsilon_A(k))$$
$$y_E(k+1)=\pi_E(y_E(k)+\alpha(k)\upsilon_E(k))$$
$$Y=\{(y_A,y_E): D_A y_A + D_E y_E \le d, y_A\ge 0, y_E\ge 0\}$$

Optimizing water reservoir (storage) control under weather variability and climate change

- Reservoir management is a sequential process. **Management decisions in preceding periods affect water availability (WA) in subsequent periods, and future inflow conditions affect current decision-making**

- Major uncertainties are in inflows q_t , $t = 1, 2, \ldots, H$



- Proper reservoir management creates benefits to multiple reservoir users:
  - Flood management
  - Reservoir storage and fisheries
  - Wetland
  - Agriculture
  - Energy Production
  - …

- We propose stochastic optimization models enabling robust solutions for managing reservoirs operating under potential extreme events and multiusers environment to supplement our proposed Decision Analysis process.
- The users are characterized by their safety (critical) water demand level
- The STO is formulated for multiple reservoir users
- The proposed approach allows solving the reservoir managing problems with moving time horizons, which are conditional on available new forecasts of water flows.

System description

- Reservoir management is a sequential process. **Management decisions in preceding periods affect water availability (WA) in subsequent periods, and future inflow conditions affect current decision-making**
- Inflow forecast q_t provides useful information on inflow, and the proper use of such forecast considerably improves reservoir management
- Deterministic balance equation for a reservoir at time *t* , $t = 1, 2, \ldots, H$

$$S_t + q_t - R_t = S_{t+1}$$

- Goal function: $$\max_{[R_1, R_2, \ldots, R_H]} F = \sum_{t=1}^{H} b_t(R_t)$$

$b_t(R_t)$	Benefit from releasing R_t at time *t*
S_t	Reservoir storage at time *t*
R_t	Release at time *t*
q_t	Inflow at time *t*
$\underline{R}_r \le R_t \le \overline{R}_t$	Maximal and minimal reservoir release
$\underline{S}_t \le S_t \le \overline{S}_t$	Maximal and minimal volume in reservoir

Reservoir management under uncertainties

B_t Benefit from releasing R_t and p_{jt} is the probability assigned to scenario q_{jt} at time *t*

Under some inflow scenario q_{jt} the required amount of release may not be met

New second-stage variables $y_{jt} \geq 0$ denote the discrepancy between the inflow and the required release

C_{jt} is a loss associated with not supplying sufficient R_t

$y_{jt} \geq 0$ are second-stage operational decisions, $\forall j$

Find optimal first-stage decisions on water release R_t^* maximizing net benefits in the face of all inflow scenarios q_{jt}

$$F = \sum_{t=1}^{T} B_t R_t - \sum_{t=1}^{T} \sum_{j=1}^{N} p_{jt} C_{jt} y_{jt} \qquad (*)$$

$$\begin{aligned} S_{jt+1} &= S_{jt} - R_t + q_{jt} \\ R_t &\leq S_{jt} + q_{jt} + y_{jt} \\ R_{\min} &\leq R_t \leq R_{\max} \\ y_{jt} &\geq 0 \quad \forall j \end{aligned} \qquad (**)$$

Reservoir management under uncertainties

Optimal second stage solutions $y^*_{jt} = \max\{0, R_t - S_{jt} - q_{jt}\}$ depend on scenarios

The problem (*) – (**) can be substituted as maximizing the implicit expected, ***E***, net-benefit function

$$f(R) = \sum_{t=1}^{T} \left[B_t R_t - EC_{jt} \max\{0, R_t - S_{jt} - q_{jt}\} \right] \qquad (***)$$

Example (T = 1) : First-stage optimal solution R^*_t is a quantile of underlying probability distribution providing robust secure levels of water supply

$T = 1$

$$f(R) = B_1 R_1 - C_1 E y_{j1}$$

$$R_1 \leq S_{j1} + q_{j1} + y_{j1}$$

$$y_{j1} \geq 0$$

Optimal second stage solutions $y^*_{j1} = \max\{0, R_1 - S_{j1} - q_{j1}\}$

The problem can be reformulated as $f(R) = B_1 R_1 + C_1 E \min\{0, S_{j1} + q_{j1} - R_1\}$

The function has non-smooth character with in general discontinuous derivatives (marginal values)

However, it can be modified and solved by LP methods

Connections with CVaR risk measures

Assume scenarios are characterized by a continuous probability density function $\rho(j)$

Goal function is a continuously differentiable

Optimal solution $R^* > 0$ is characterized by $f'(R) = 0$:

$$f'(R) = B_1 - C_1 \operatorname{Prob}[S_{j1} + q_{j1} \le R_1] = 0$$

$$f'(R) = \operatorname{Prob}[S_{j1} + q_{j1} \le R_1] = B_1 / C_1$$

If $B_1 < C_1$, there exist $R_1 = R^* > 0$ for water supply in period 1 characterized by the quantile implicitly defined by the whole structure of reservoir model including forecast of inflow q_{j1}, uncertainties of storage S_{j1}, the structure of costs and benefits

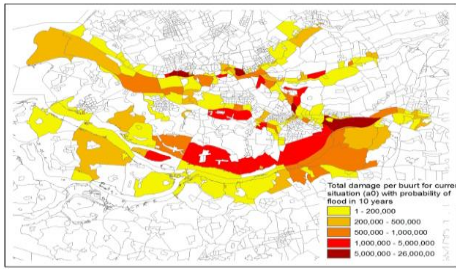
It is important that the solution is defined by the quantile, that is critical for controlling reservoirs safety under uncertainties and extreme events because, as it is well known, the use of mean values may be dramatically misleading.

The optimal value of functions $f(R^*)$ characterizes CVaR risk measures

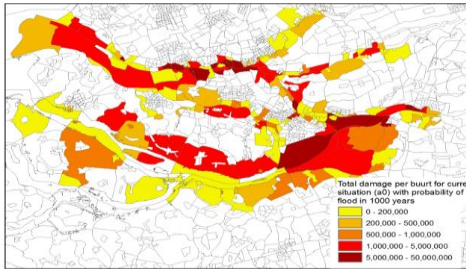
Flood management in the Netherlands

Case-study region (this case study considers only the areas outside the primary embankments.

Areas outside the main protections system	Protected areas within a dike-ring
Flood and damage characteristics	
Government does not guarantee any safety standards. Actual return periods vary between 1:5, 1:10 years to 1:100, 1:1000 years or less frequent (e.g. 1:10000 for new harbor areas)	Safety standards assigned by law: 1:200 to 1:1250 years – river floods 1:2000 and 1:4000 for the estuary (tidal rivers) 1:4000- to 1:10000 years – coastal floods.
Probability of flood is location-specific and may be much higher than the official safety standard in the neighboring protected areas.	One homogeneous safety standard for the whole dike-ring.
Properties are elevated above sea level, i.e. on dunes, man-made high elevation grounds, etc.	Many developments inside dike rings are below sea level (up to -6 meters).
Flood water comes with low velocity and goes away quickly.	Flood water comes with high velocity and stays for a long period.
Flood protection and roles of different parties	
Developments are at the risk on individuals (households or firms). Municipalities may prohibit some socially-vital activities in these areas, e.g. hospitals.	Government is responsible to assure safety standards prescribed by law.
Individuals are responsible for their own protection and damage in the case of flooding.	Government refund any possible damage from a flood event.
Flood insurance does not exist but is argued to be financially feasible [44].	Until recently flood insurance did not exist. First contracts to insure flood risks became available in 2013 [3]. The issue is debatable since some consider it unfeasible [30], [32] while others think it is feasible under various reinsurance schemes [1].

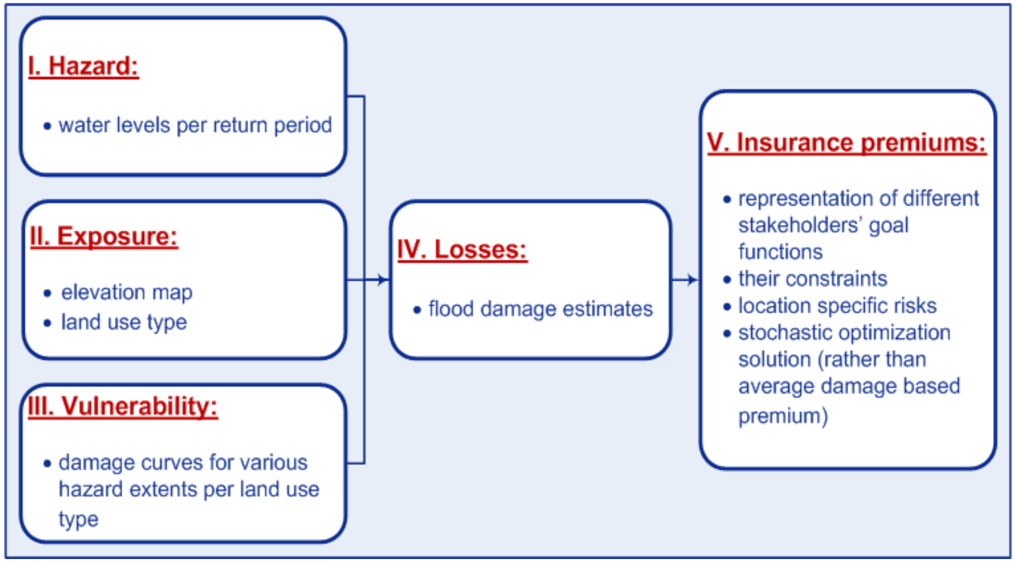


Losses, 10-yr. flood

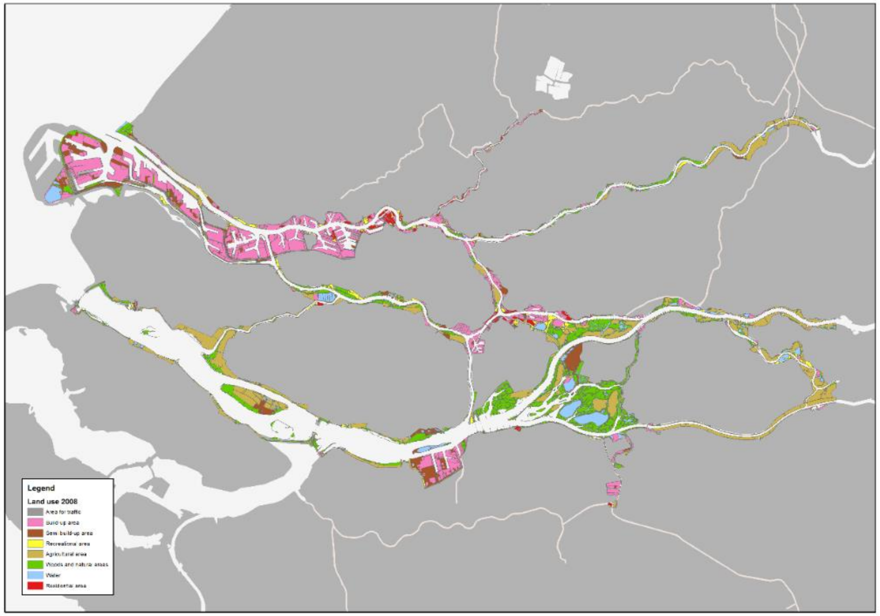


Losses, 1000-yr. flood

Land use in the Rijnmond-Drecthsteden region (the colored area is the area outside the main protection system).



Scheme of modules and data flows.

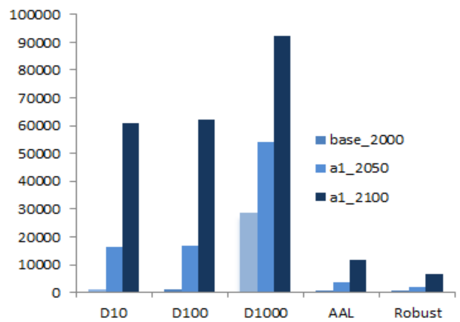


Instead of using Average Annual Damage" approach, we design percentile-based premiums based on the following goal function reflecting vital indicators of: the government, insurer, and insured:

$$F(x) = E\sum_j (1-q_j)L_j + \alpha E\max\{0,\sum_j (q_jL_j - \pi_j)\} + \beta\sum_j E\max\{0,\pi_j - q_jL_j\}$$

$\{\sum_j (\pi_j - q_jL_j(\omega)) < 0\}$ - non-overcompensations by insurers

$\{\pi_j - q_jL_j(\omega) > 0\}$ - non-overpayments by individuals



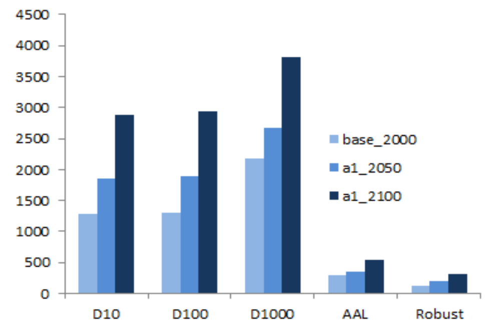
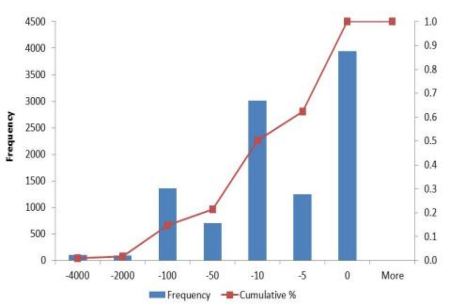


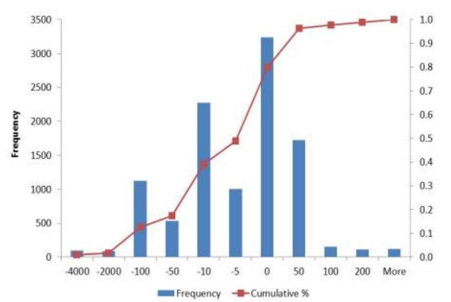
Figure a:

Figure b:

Total flood damages for 3 return periods: D10, D100, D1000 correspond to 10-, 100-, and 1000- year floods, respectively, in 2000, 2050, 2100 years; and total AAL and Robust premiums (per year).

Insurer's balance between premiums and coverages



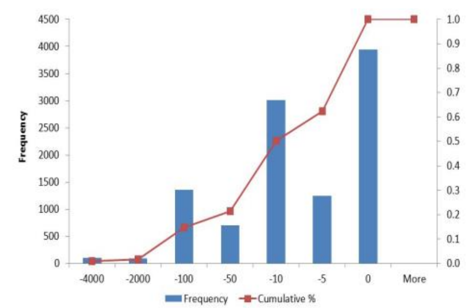


Non-overpayments by economic agents (firms and households)

a: robust premiums, $\alpha = 1$.

b: robust premiums, $\alpha = 100$.

$$\{\pi_j - q_jL_j(\omega) > 0\}$$



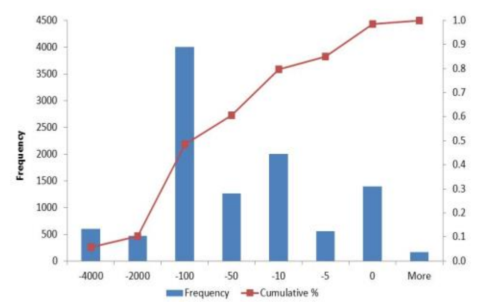


Figure a: Non-overcompensations by insurance companies under Robust premiums

b: Non- overcompensations by insurance companies under AAL premiums

$$\{\sum_j (\pi_j - q_jL_j(\omega)) < 0\}$$

Robust Rescaling Methods for Integrated Water, Food, Energy Security Management under Systemic Risks and Uncertainty

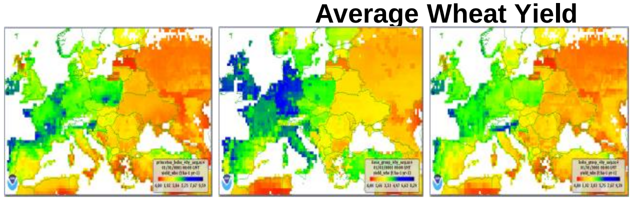
Motivation for downscaling

Systems analysis of global change (including climate) processes requires new approaches to integrating and rescaling of models, data, and decision-making procedures between various scales. High spatial resolution land use and cover change projections are also required as one of the crucial inputs into Global Circulation Models.

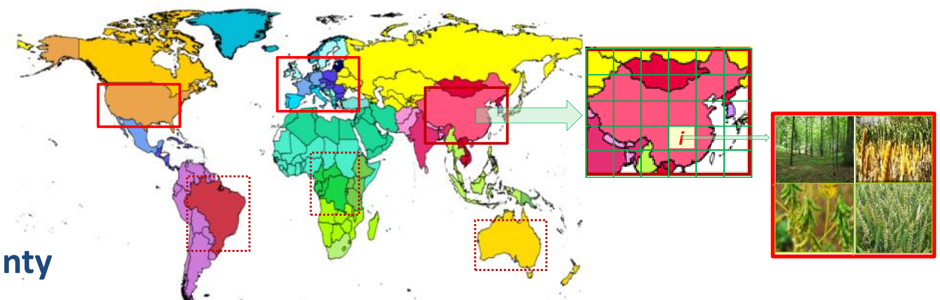
Downscaling can be termed as a **"New Estimation Problem"**. While traditional statistical estimation problems are based on the ability to obtain observations from unknown true sampling model, for downscaling (and upscaling) problems we may have only **aggregate, uncertain data with very restricted samples of real local observations**.

Downscaling enables interface and compatibility between global and local models and decisions under uncertainty of global and local data and processes.

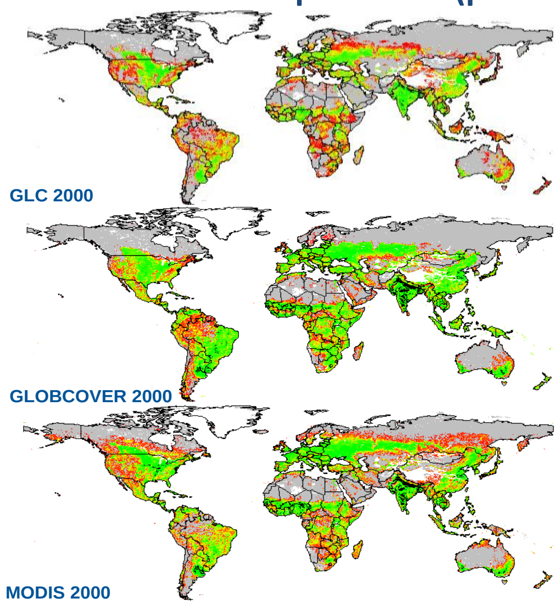
Average Wheat Yield



Princeton (BOKU) GRASP (IIASA) GRASP (BOKU)



Large uncertainty in local data and processes (priors)



Robust downscaling is being applied for data harmonization, designing hybrid maps, downscaling regional and global projections.

The procedure has been integrated with (stochastic) Global Biosphere Model (Havlík et al. 2011; Ermolieva et al., 2015, 2014) for the analysis of food, energy, water security issues and sustainable development trends at global, regional, country and local levels.

Robust non-Bayesian probabilistic Cross-entropy: treatment of uncertainties

Instead of a uniquely defined prior there is a plausible set of these distributions.

Prior distributions **depend on various "environmental" parameters** which may **not** be **known exactly**.

The estimation of local changes consistent with available aggregate data is formulated as **probabilistic inverse** (from aggregate to local data) problem in the form of, in general, **non-convex stochastic cross-entropy minimization model**.

By using a specific reparametrization and duality relations for a nested optimization subproblem, the model is reformulated as **nested convex stochastic cross-entropy minimization problem**.

The procedure treats two main cases of priors: **compound and non-Bayesian priors**.

Conclusions

We provided and overview and illustration of available and under development methods and models for decision-making under uncertainty and (systemic) risks in interdependent land use, water, financial (insurance) and other systems.

Systemic risks arise due to:
systemic imbalances among interdependent systems,
inadequate storages and supply-demand relationships,
uncertainty and risk ignorance,
Deterministic independent systems' analysis instead or risk-based approaches to nexus modeling and security management.

While discussing particular approaches, we highlighted the importance of integrated (cross-sectorial) analysis.

Other aspects we suggest for consideration:
complex multivariate decision-dependent analytically intractable risk distributions,
Robust strategic ex-ante and operational ex-post decisions vs scenario-dependent decisions,
Possible lock-in solutions and irreversibility situations,
Long horizons of evaluations,
New approach to discounting, endogenous discounting.

Selected relevant publications

Ermolieva, T., Zagorodny, A.G., Bogdanov, V.L., Havlik, P., Rovenskaja, E., Komendantova, N., Knopov, P.S. (2025 forthcoming) Integrated solutions and distributed models' linkage procedures for food-energy-water-environment NEXUS security modeling and management.

Komendantova, N., Ermolieva, T., Zobeydi, T., Armas, I., Toma-Danila, D., Hürlimann, M. Integrated modeling for managing catastrophic risks: vulnerability analysis and systemic risks management (2025 forthcoming) .

Ermolieva, T., Havlík, P., Ermoliev, Y., Mosnier, A., Obersteiner, M., Leclère, D., Khabarov, N., Valin, H. and Reuter, W. (2016) Integrated Management of Land Use Systems under Systemic Risks and Security Targets: A Stochastic Global Biosphere Management Model. Journal of Agricultural Economics, 67 (3). pp. 584-601.

Ermoliev, Y., Komendantova, N., & Ermolieva, T. (2023). Energy Production and Storage Investments and Operation Planning Involving Variable Renewable Energy Sources A Two-stage Stochastic Optimization Model with Rolling Time Horizon and Random Stopping Time. In: *Modern Optimization Methods for Decision Making Under Risk and Uncertainty*. Eds. Gaivoronski, A., Knopov, P., & Zaslavskyi, V., Taylor & Francis. ISBN 9781003260196 10.1201/9781003260196-13.

Ermolieva, T., Havlik, P., Ermoliev, Y., Khabarov, N., & Obersteiner, M. (2021). Robust Management of Systemic Risks and Food-Water-Energy-Environmental Security: Two-Stage Strategic-Adaptive GLOBIOM Model. Sustainability 13 (2) e857. 10.3390/su13020857.

Ermolieva., Havlik,P., Lessa-Derci-Augustynczik,a., Frank,S., Deppermann,A., Nakhavali, A., Balkovic,J., Skalsky,R., Komendantova, N. Robust statistical estimation and two-stage STO: quantile regression EPIC meta-model of Soil Organic Carbon for robust decision making with GLOBIOM

Ermolieva, T., Zagorodny, A., Bogdanov, V.L., Wang, G., Havlik, P., Rovenskaya, E., Komendantova, N., Kahil, T., et al. (2023). Consistent linkage of distributed food, water, energy, environmental (FWEE) models: perspectives of data and modeling platform for integrated FWEE security NEXUS analysis and planning. In: *EGU General Assembly 2023*, 23-28 April 2023, Vienna.

Ermoliev, Y., Komendantova, N., & Ermolieva, T. (2023). Energy Production and Storage Investments and Operation Planning Involving Variable Renewable Energy Sources A Two-stage Stochastic Optimization Model with Rolling Time Horizon and Random Stopping Time. In: *Modern Optimization Methods for Decision Making Under Risk and Uncertainty*. Eds. Gaivoronski, A., Knopov, P., & Zaslavskyi, V., Taylor & Francis. ISBN 9781003260196 10.1201/9781003260196-13.

Ermolieva T, Boere E, Biewald A, Havlik P, Mosnier A, Leclere D, Valin H, Frank S, et al. (2019). Addressing climate change adaptation with a stochastic integrated assessment model: Analysis of common agricultural policy measures. Financial Statistics Journal 1 (2) DOI:10.24294/fsj.v0i0.913.

Ermolieva, T., Ermoliev, Y., Havlik, P., Derci Augustynczik, A.L., Komendantova, N., Kahil, T., Balkovič, J., Skalský, R., et al. (2023). Connections between robust statistical estimation, robust decision making with two-stage stochastic optimization, and robust machine learning problems. *Cybernetics and systems analysis* 59 (3) 33-47.

Ermolieva, T., Ermoliev, Y., Komendantova, N., Norkin, V., Knopov, P., & Gorbachuk, V. (2023). Linking Catastrophe Modeling and Stochastic Optimization Techniques for Integrated Catastrophe Risk Analysis and Management. In: *Modern Optimization Methods for Decision Making Under Risk and Uncertainty*. Eds. Gaivoronski, A., Knopov, P., & Zaslavskyi, V., pp. 15-50 Taylor & Francis. ISBN 9781003260196 10.1201/9781003260196-2.

Wildemeersch, M., Tang, S., Ermolieva, T., Ermoliev, Y., Rovenskaya, E., & Obersteiner, M. (2022). *Containing the Risk of Phosphorus Pollution in Agricultural Watersheds. Sustainability* 14 (3) e1717. 10.3390/su14031717.