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Der Blick über den Zaun: KI als Gamechanger in der Landwirtschaft?

44. Freiburger Winterkolloquium Forst und Holz | Albert-Ludwigs-Universität Freiburg | 30.01.2025

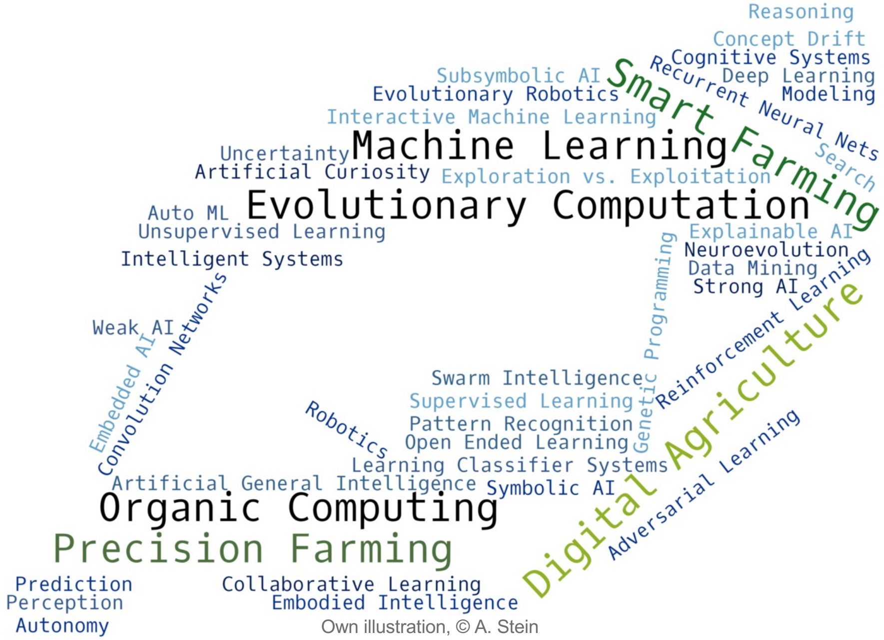
JProf. Dr. Anthony Stein

Institute of Agricultural Engineering
& Computational Science Hub (CSH)

Dept. of Artificial Intelligence in Agricultural Engineering

Outline

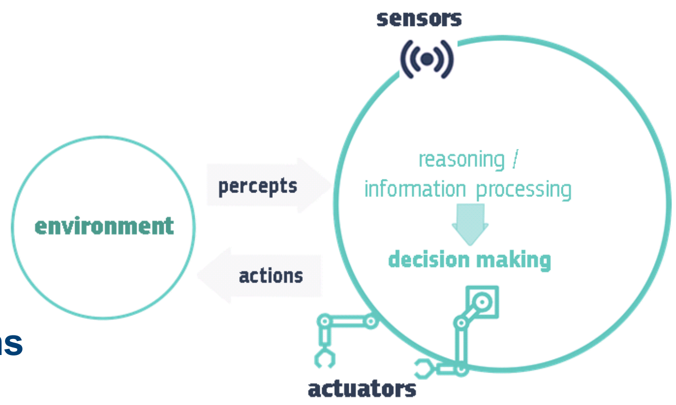
- **AI in agriculture?**
- Today: Agricultural AI applications
- Tomorrow: Research activities
- Aspects of getting there

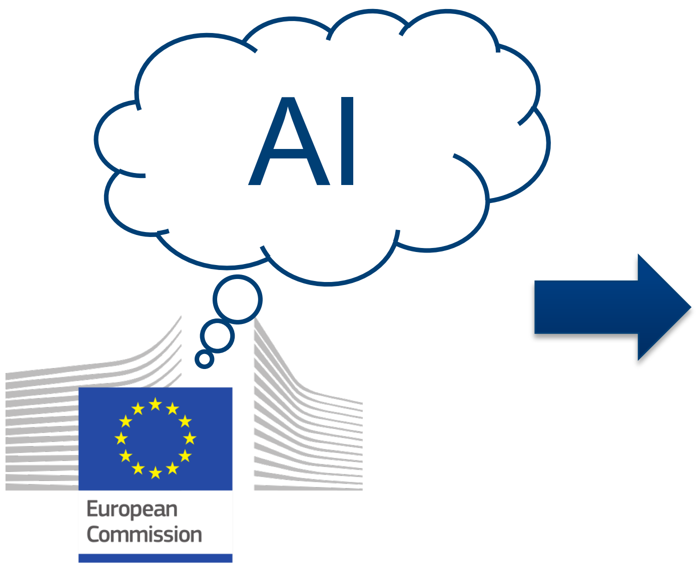


Own illustration, © A. Stein

Artificial Intelligence?

Definition of European Commission's High-level Expert Group





- **Systems** designed by **humans**
- Given complex **goal(s)**
- Act in **physical** or **virtual** dimension
  - By **perceiving** environment (sensors, data acquisition)
  - **Deciding** best **actions** to reach the goal
- Can **analyze, learn, reason, adapt**

- **Scientific** discipline
- Incl. several **approaches:**
  - Machine learning
  - Reasoning
  - and Robotics

- Integration into **cyber-physical systems**

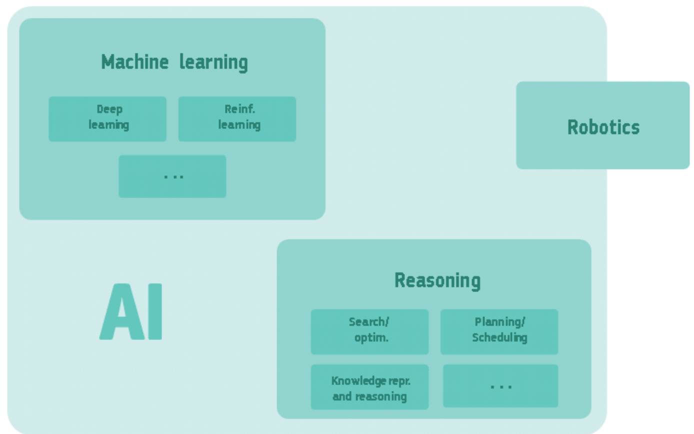


Figure sources: The European Commission's HIGH-LEVEL EXPERT GROUP ON ARTIFICIAL INTELLIGENCE, 2019, Available online: https://digital-strategy.ec.europa.eu/en/library/ethics-guidelines-trustworthy-ai (last 25.01.2025)

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Artificial Intelligence?

AI Act defines AI as follows

EU Artificial Intelligence Act

- "(1) 'AI system' means a machine-based system that is designed to operate with varying levels of autonomy and that may exhibit adaptiveness after deployment, and that, for explicit or implicit objectives, infers, from the input it receives, how to generate outputs such as predictions, content, recommendations, or decisions that can influence physical or virtual environments; Related: **Recital 12**"

Source: https://artificialintelligenceact.eu/article/3/ (last accessed 25.01.2025)

Artificial Intelligence?

AI Act defines AI as follows – **Recital 12**

EU Artificial Intelligence Act

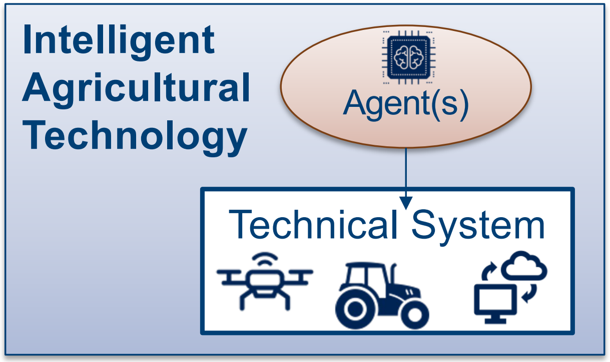
Source: https://artificialintelligenceact.eu/recital/12/ (last accessed 15.10.2024)

The notion of ‘AI system’ in this Regulation should be clearly defined and should be closely aligned with the work of international organisations working on AI to ensure legal certainty, facilitate international convergence and wide acceptance, while providing the flexibility to accommodate the rapid technological developments in this field. Moreover, the definition should be based on key characteristics of AI systems that **distinguish it from simpler traditional software systems or programming approaches and should not cover systems that are based on the rules defined solely by natural persons to automatically execute operations**. A **key characteristic of AI systems** is their capability to **infer**. This capability to infer refers to the process of **obtaining the outputs, such as predictions, content, recommendations, or decisions, which can influence physical and virtual environments, and to a capability of AI systems to derive models or algorithms, or both, from inputs or data**. The **techniques** that enable inference while building an AI system include **machine learning** approaches that learn **from data** how to achieve certain **objectives**, and **logic- and knowledge-based approaches** that infer from **encoded knowledge or symbolic representation** of the task to be solved. The capacity of an AI system to infer transcends basic data processing by enabling learning, reasoning or modelling. The term ‘**machine-based**’ refers to the fact that **AI systems run on machines**. The reference to explicit or implicit objectives underscores that **AI systems can operate according to explicit defined objectives or to implicit objectives**. The objectives of the AI system may be different from the intended purpose of the AI system in a specific context. For the purposes of this Regulation, **environments** should be understood to be the **contexts in which the AI systems operate**, whereas **outputs generated by the AI** system reflect different functions performed by AI systems and include **predictions, content, recommendations or decisions**. AI systems are designed to operate with **varying levels of autonomy**, meaning that they have some degree of independence of actions from human involvement and of capabilities to operate without human intervention. The **adaptiveness** that an AI system could exhibit after deployment, refers to **self-learning capabilities**, allowing the **system to change while in use**. AI systems can be used on a **stand-alone basis** or as a **component of a product**, irrespective of whether the system is **physically** integrated into the product (**embedded**) or serves the **functionality** of the product without being integrated therein (**non-embedded**).

Our perspective on AI in agriculture

Pursuit of building **Intelligent Agricultural Technology**

"AI in Agriculture is the **scientific discipline** of designing intelligent **agents** *(AI programs)* for utilization in **technical systems** of a **digitized agriculture** with the aim to **relieve farmers** of tedious, time-consuming, risky or overly complex tasks and at the same time **optimizing agricultural processes** in terms of their resource **efficiency**, working **quality, resilience** and in turn **sustainability**."



Own illustration, © A. Stein

- **"Technical system":** An engineered system built for serving a certain purpose, i.e., to achieve a certain task. Examples from agriculture:
  - Tractors and adaptable implements
  - UAVs for remote sensing / crop monitoring
  - Field robots for plant production purposes
  - Milking robots or barn cleaning robots
  - Climate and ventilation control systems
  - Surveillance systems in pigsty or cattle barns
  - Agricultural Information Systems (FMIS, GIS, etc.)
  - …
- **"Intelligent system":** A technical system endowed with AI agents (i.e., programs) to possess properties such as
  - ***adaptivity*** to varying conditions (e.g., weather, soil)
  - ***robustness*** against unexpected events / disturbances
  - ***flexibility*** to changed goals and constraints (e.g. due to seasonal or policy changes)

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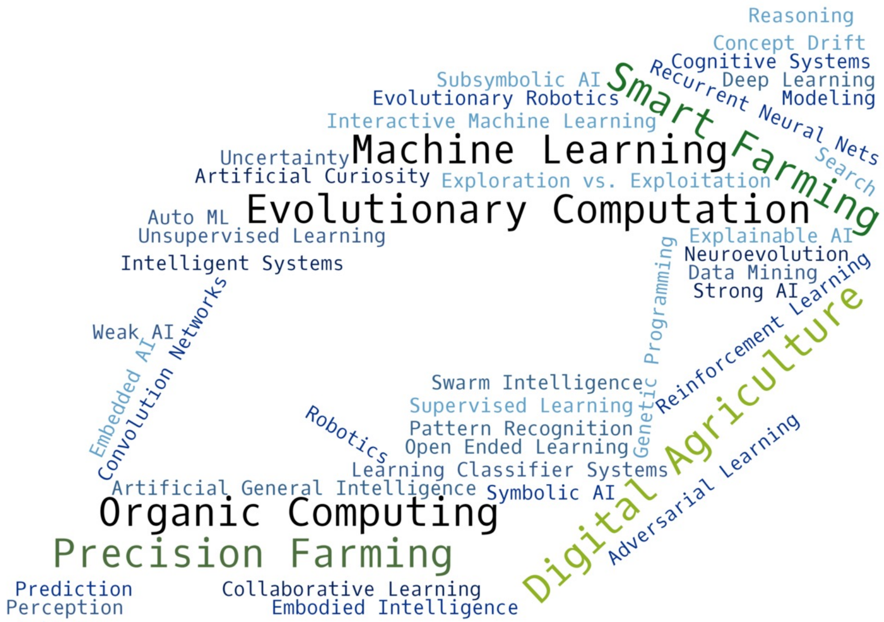

Own illustration, © A. Stein

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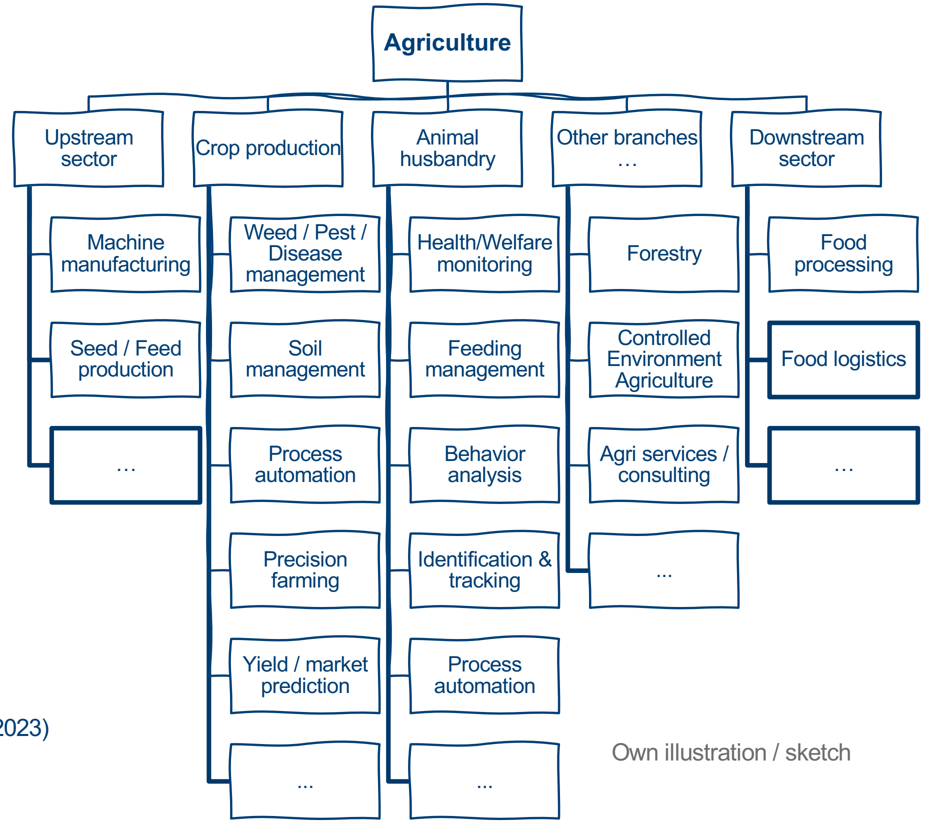
Applications of AI in agriculture

- AI's **potential omnipresent** in agriculture

- **Enabling trends and drivers:**
  - Ongoing **disruptive AI advancements** since 2010s
  - **Data availability** due to **smart/digital agriculture**
  - **Continually improving sensor technology**
  - **Embedded computing units** have become more computationally **powerful** and **`AI-ready'**
  - Combined with more **efficient** and **`off-the-shelf' available AI models**
  - **Research programs** have been funded recently by institutions such as BMEL, BMWK, BMBF, DFG …

- Most applications in crop production today (cf. Ryan et al. 2023)
- Much AI research in livestock and other sectors



Own illustration / sketch

Promises of AI in agriculture

Current technology still highly depends on **manual operations** and **decisions**

- **Limited human capacity** for manual analysis
- e.g., determining the nutritional state and demand of every individual plant

➢ ↓ **human labor** through higher automation

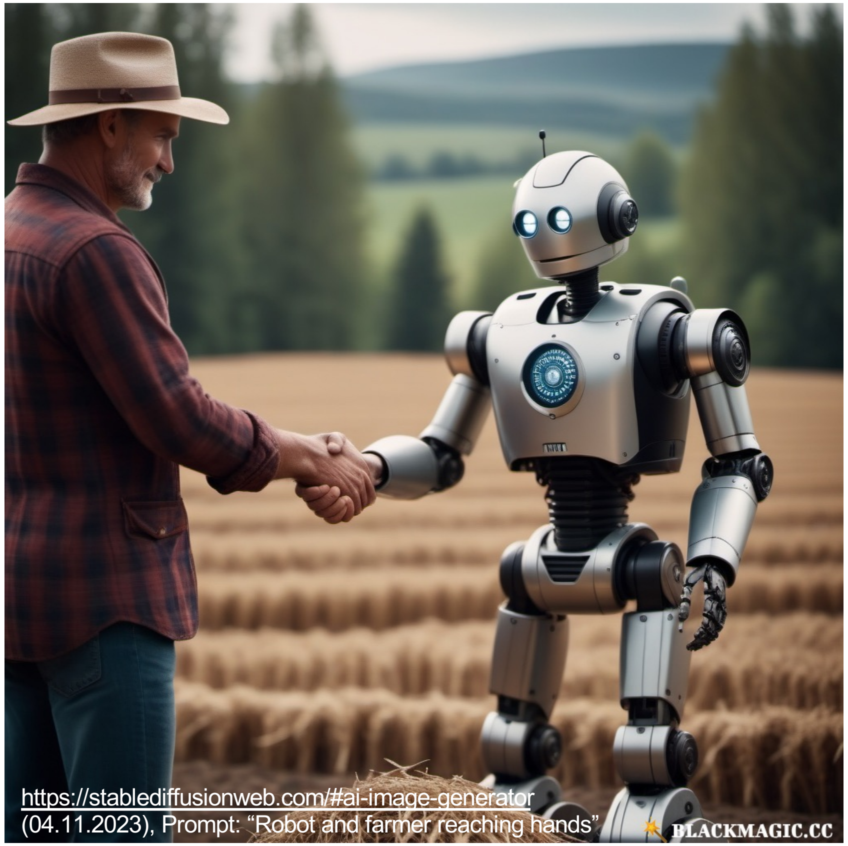
- Addresses **labor shortage**
- Role shift: **Concentrate** on **important tasks**

➢ ↑ **analysis** and **decision capabilities**

- Better **decision support** and **advice**
- Higher **spatio-temporal resolution**

➢ ↑ **efficiency** + **sustainability** + **resilience**

- Ensure **food security** (higher productivity)
- Still **reducing negative environmental impacts**



https://stablediffusionweb.com/#ai-image-generator (04.11.2023), Prompt: “Robot and farmer reaching hands”

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`AgBots' – Robots for agricultural field work

Examples of two commercially available types

- Smaller, self-propelled machines specialized to (few) specific task(s)
- Driverless tractor with conventional implements

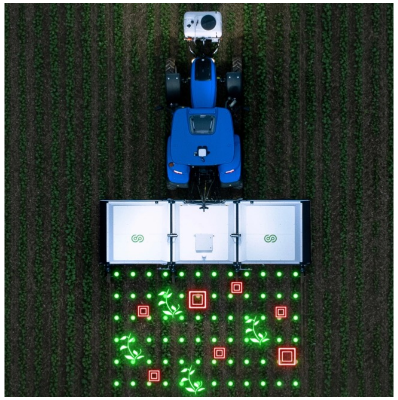
Source: FarmingGT Video, **Farming Revolution Website**,
URL: https://farming-revolution.com/static/54e6aa1256cc235d368b1777eb4f24f1/hero_15s.mp4 (25.01.2025)

Source: AgXeed Video, **Agxeed** Website, URL: https://www.agxeed.com/wp-content/uploads/2024/05/Ploughing-testingusecase.mp4 (25.01.2025)

AI-assisted crop production

Weed control solutions

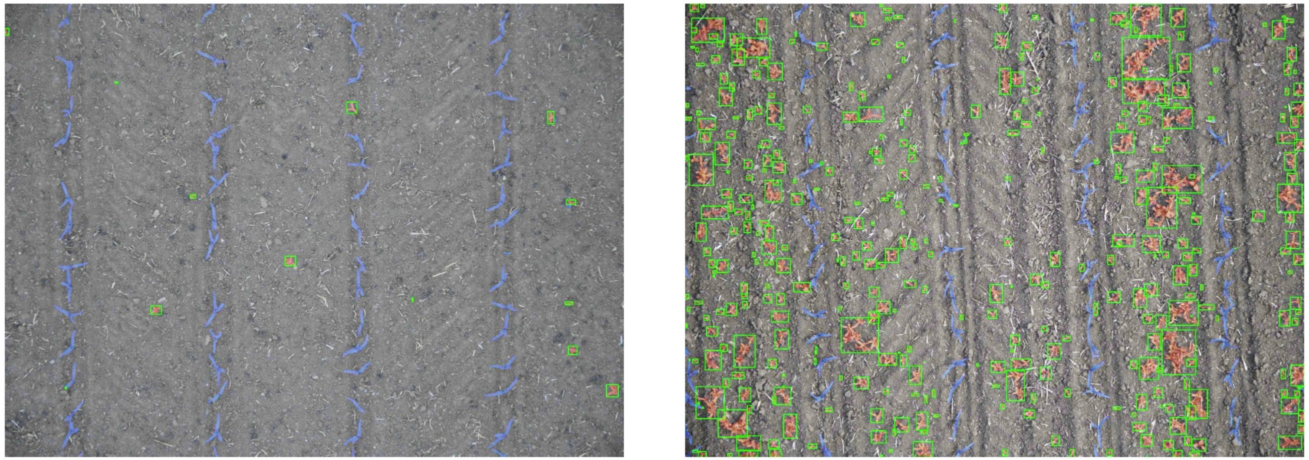
- AI-based weed detection
- Plant-individual precision and application
- Herbicide savings up to ~90% possible
- Variants:
  - **One-stage:** New smart implements
  - **Two-stage**: Air-borne mapping + application



Source: **Ecorobotix** Website, URL: https://ecorobotix.com/de/plant-by-plant-ki-software/ (last 25.01.2025)

Source: **Rumex GmbH** Website,
URL: https://rumex-gmbh.de/images/03_Animation.mp4 (last 25.01.2025)

Source: **SAM DIMENSION**, permission to reuse material granted



Unkrauterkennung (rot) mittels “künstlicher Intelligenz” Luftbildern in Mais (blau) zu EC 13. Grüne Rechtecke zeigen erkannte Unkrautpositionen. Links wenig Verunkrautung, rechts starke Verunkrautung.

AI-assisted crop production

Tools to support harvesting

- Robotic fruit harvest with tethered drones
- Automated loading during forage harvest
- In-process grain quality assessment
- Using computer-vision and machine learning:
  - Classifying and localizing ripe fruits
  - Detecting trailer and fill status → Discharge arm control
  - Segmenting broken grain and foreign material

Source: **Tevel-Tech** Press Release, URL: https://www.tevel-tech.com/press-release-tevel-partners-with-unifrutti-expands-to-south-america/ (25.01.2025)

Source: **John Deere** Website, URL: https://www.deere.com/assets/images/region-2/campaigns/ag-turf/grain-quality-guaranteed/r4f000511-c1-lsc.jpg (25.01.2025)

AI-assisted livestock farming

Herd management and tools

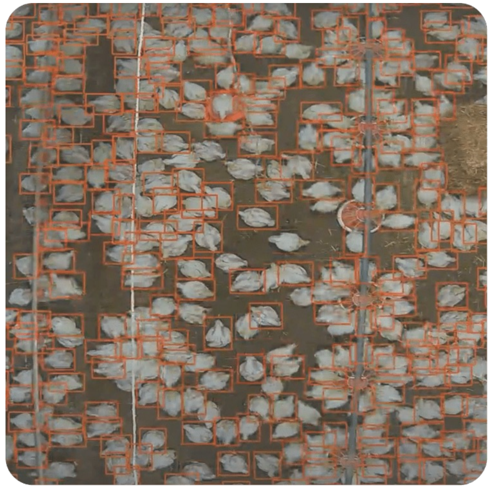
- Animal health monitoring and tracking
  - E.g., Lameness, calving
- Automated recognition of parameters
  - Herd activity and animal distribution
  - Average weight estimation
- Barn climate reports and control
- Robotic applications:
  - Forage robots
  - Floor / barn cleaners
  - Milking robots

➢ Recommendation to farmers

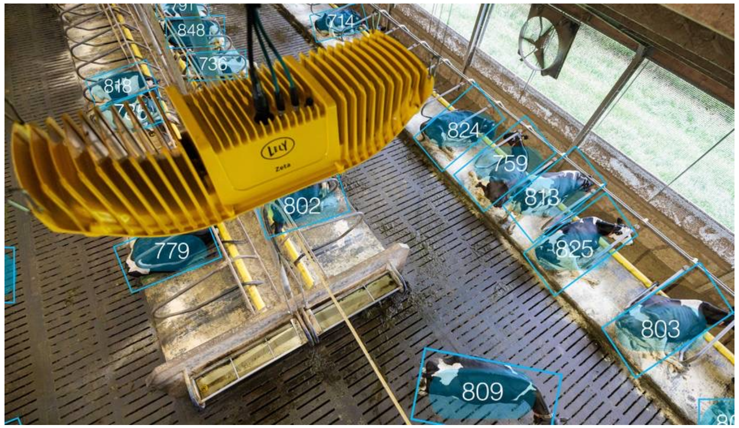
➢ Higher husbandry process automation

➢ Better and more timely insights on barn dynamics

Source: **Big Dutchman WeightCheck**, Website, URL: https://www.bigdutchmanusa.com/en/pig-production/products/growing-and-finishing/sorting/weightcheck/ (26.01.2025)



Source: **Vetvise** Website, URL: https://i0.wp.com/vetvise.com/wp-content/uploads/2024/04/Website_Gefluegel-3.png?resize=768%2C768&ssl=1 (last 26.01.2025)



Source: **Lely** Zeta KI-Stallmonitor, Lely Website, URL: https://www.lely.com/media/filer_public_thumbnails/filer_public/a9/f9/a9f906ed-f27c-4157-b4fc4c7b1fbe35dc/lely-zeta-i-barn-608120-2-rg.jpg__900x520_q70_crop-smart_subsampling-2_upscale.jpg (26.01.2025)

Source: **HIT Active Cleaner** Pferdeäpfel-Roboter, URL: https://aktivstall.de/wp-content/uploads/2023/01/aktivstallroboter_800_1.jpg (26.01.2025)

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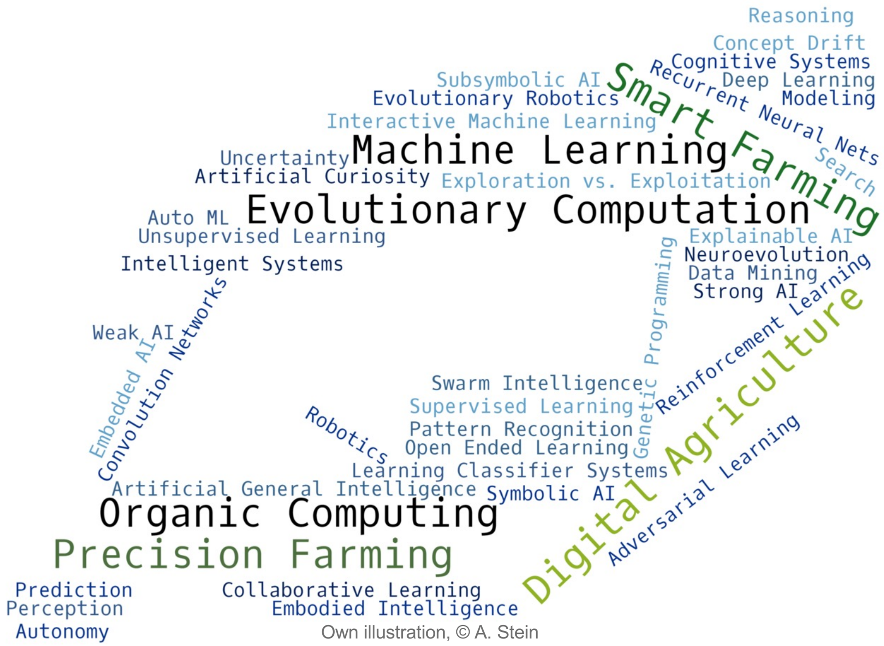


Own illustration, © A. Stein

Artificial Intelligence in Agricultural Engineering

Our department's research statement

> Our aim is to make an ***information technology-based*** contribution to meeting the pressing ***challenges*** of ***today's*** and of a ***future-proof digital agriculture***.

I.
Robust Machine Learning
in agricultural machines and systems

II.
Swarm Robotics
for a scalable & highly precise crop production

III.
Agent-based Architectures
for controlling complex systems of digital agriculture

IV.
Ressource-efficient AI/ML
for agricultural data handling, analysis & model explanation

AI Toolbox

- Simulation-based ML
- Reinforcement Learning
- Evolutionary Computation
- Distributed AI
- Organic Computing
- Interpretable ML
- Auto ML
- MLOps
- …
- Active Learning

I. Robust machine learning & III. Agent-based Architectures

Intelligent Secondary Tillage Control

- **Observation**
  - Agricultural machines often not fully utilized → *Performance Gap*

- **Challenges**
  - Controlling these machines optimally is complex
  - Variability in soil conditions would require continual monitoring and adaptation of machine parameters

➢ **Approach**
  - Intelligent Control Architecture
    → *Organic Computing*
  - Model the environment-machine response
    → *Deep Learning*
  - Train an intelligent agent to control the machine
    → *Reinforcement Learning*

KINERA
Künstliche Intelligenz für eine effiziente und resiliente Agrartechnik

Gefördert durch Bundesministerium für Ernährung und Landwirtschaft aufgrund eines Beschlusses des Deutschen Bundestages

Projektträger Bundesanstalt für Landwirtschaft und Ernährung

- **Project goals:**
  - **Digitization** of the **sowing process**
  - Development of an **ICT architecture** with a focus on **fault tolerance** for **resilient** farm operations
  - **Performance gap reduction** of the involved machines/implements (on farm and inter-farm)
  - Reduce **operation complexity** for the driver

Dept. 440g AI in Agricultural Engineering (coordination)
Dept. 440d Technology in Crop Production
Dept. 530d Information Systems 2

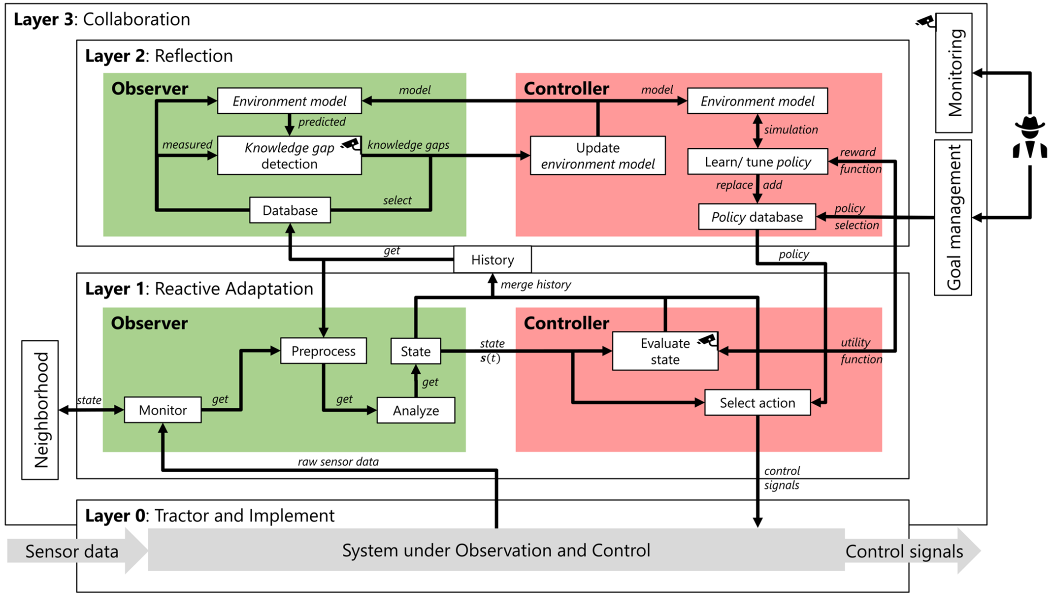
exatrek
SMART SITE SOLUTIONS

Associate partners:
HORSCH
VDMA Landtechnik
CLAAS

I. Robust machine learning & III. Agent-based Architectures

Intelligent Secondary Tillage Control

- Design of an intelligent agent architecture
- Based on the principles of *Organic Computing*
- **Observer/Controller-Architecture**

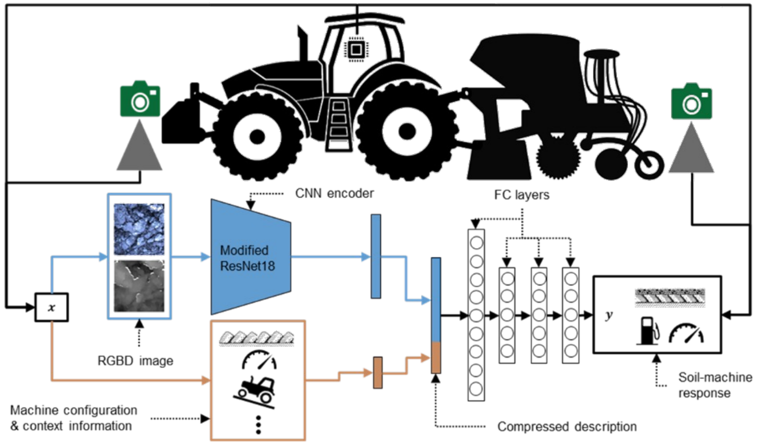


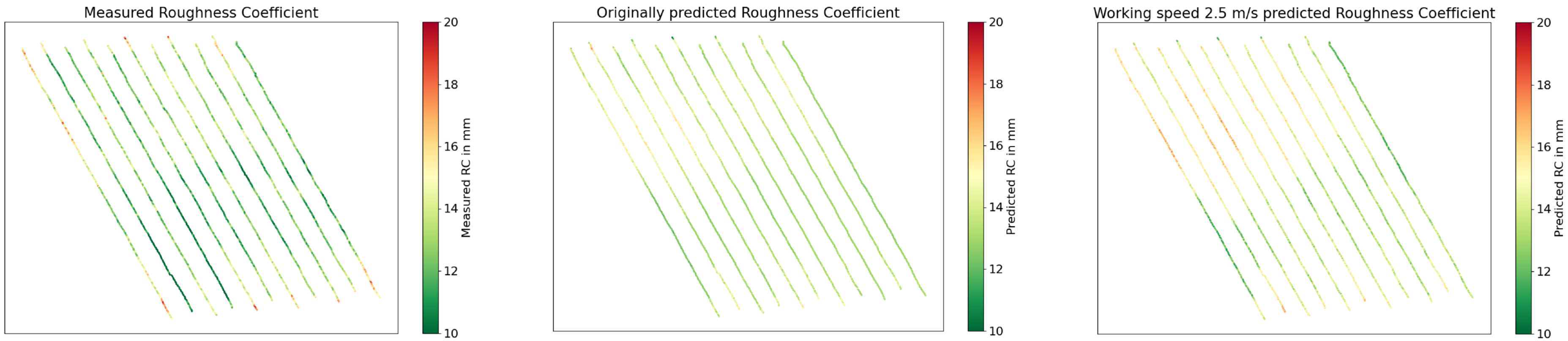
Stein, A., & Boysen, J. (2025). Organic Computing for Intelligent Agricultural Technology: Perspective and Case Study. Agricultural engineering.Eu, 80(1). https://doi.org/10.15150/ae.2025.3331

I. Robust machine learning & III. Agent-based Architectures

Intelligent Secondary Tillage Control

- *Soil-machine response* model
  - Collect in situ dataset in the real world
- Predicts next environment state based on state and machine configuration
  - Soil roughness, Engine fuel rate, Engine torque utilization
- Basis for creating control agent using **model-based Reinforcement Learning**





Jonas Boysen, Lucas Zender, Anthony Stein, Modeling the soil-machine response of secondary tillage: A deep learning approach, Smart Agricultural Technology, Volume 6, 2023, 100363, https://doi.org/10.1016/j.atech.2023.100363

II. Swarm robotics on agricultural fields

Why agricultural swarm robotics?

- Scaling potential → ***flexibility***
- Less depedence on single machines but compensation of failed machines → ***robustness***
- Smaller machines → ***soil protection***

- High potential seen in **small-scale cultivation** or **spot farming systems**

- Smaller machines usually **work at lower speeds** but can reach **higher working quality** (cf. e.g., Griepentrog & Stein (2024))

- **Area capacity** (dt. Flächenleistung) can be achieved by **increasing number of robots**

- Example of a small agricultural robot `**Phoenix**' developed in Hohenheim

The problem... we only have one of it ;)

Source: Phoenix robot, H.W. Griepentrog, Uni Hohenheim, FG Verfahrenstechnik in der Pflanzenproduktion.

Griepentrog HW, Stein A (2024) Comparison of Robot Concepts for New Sustainable Crop Production Systems. Smart Agricultural Technology :100499. https://doi.org/10.1016/j.atech.2024.100499

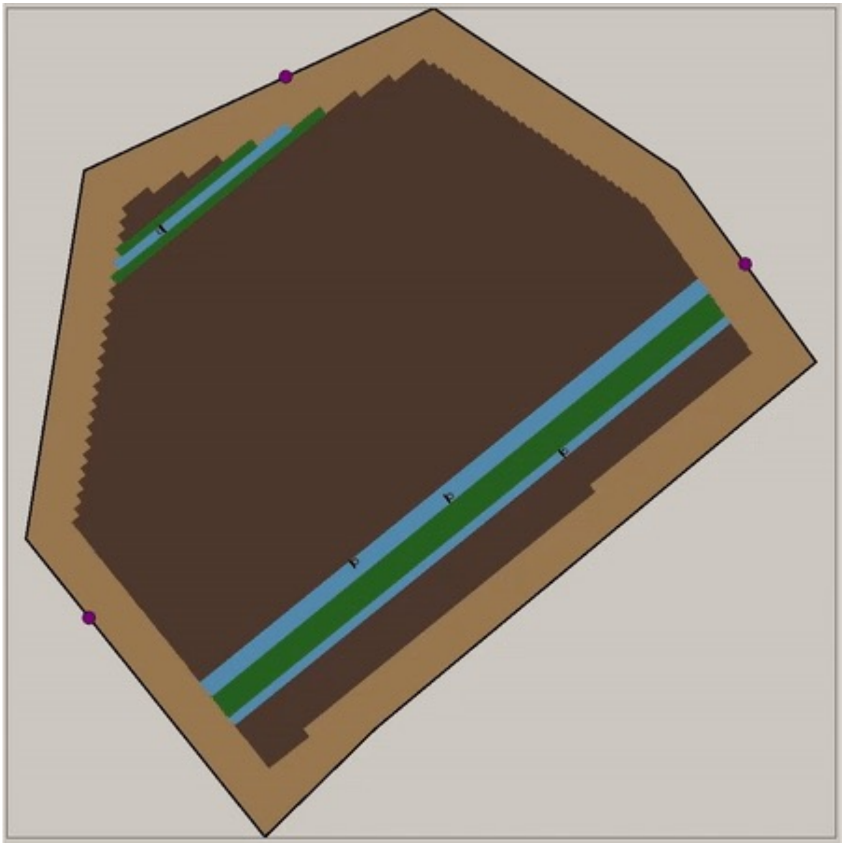
II. Swarm robotics on agricultural fields

First approach: Simulation-based study

- **Simulate** scalable robot **swarms** at **process level**
  - Energy charge level & consumption
  - Seed level & seed rate
  - Logistic points to refill & charge
  - Working width
  - Turning radius
  - → according to the model of the **Phoenix robot**

- **Comparison**: Swarm vs. conventional machine
  - **Metrics** for determining the potential
  - Area capacity $\frac{machined\ area}{overall\ work\ time}\left[\frac{ha}{h}\right]$
  - Field efficiency $\frac{effective\ work\ time}{overall\ work\ time}$ [%]

- **Evaluate:**
  - Performance of **fully decentralized swarm coordination** (*self-organization*) with **centralized** and **hybrid** approaches
  - Impact of **individual robot failures** on performance metrics



Source: Swarm robot simulation, Dept. Artificial Intelligence in Agricultural Engineering, Uni Hohenheim

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IV. Resource-efficient AI for agricultural applications

GenAI-based training data creation

- **Observation**:
  - AI models need **vast amounts** of **representative training data** to become robust
- **Challenges**:
  - Manual **annotation / labelling effort too high**
  - Lack of diversity in training sets → heterogeneous local conditions
  - Imbalances in the class distributions → e.g., visible weeds vs. crops

➢ **Approach**: Increase *data efficiency*
  - Annotate fewer training images
  - Use **GenAI models** to generate synthetic training data
  - **Mix** with **real data** to improve downstream task

Project `HoPla'

PHOTONIK FORSCHUNG DEUTSCHLAND

GEFÖRDERT VOM Bundesministerium für Bildung und Forschung

- Increase weed detection accuracy and speed
- Focus on economically highly relevant crops
- Our contributions:
  - Reduce manual data annotation effort (*data efficiency*)
  - Compress large AI models and distill knowledge into computationally efficient models (*inference efficiency*)

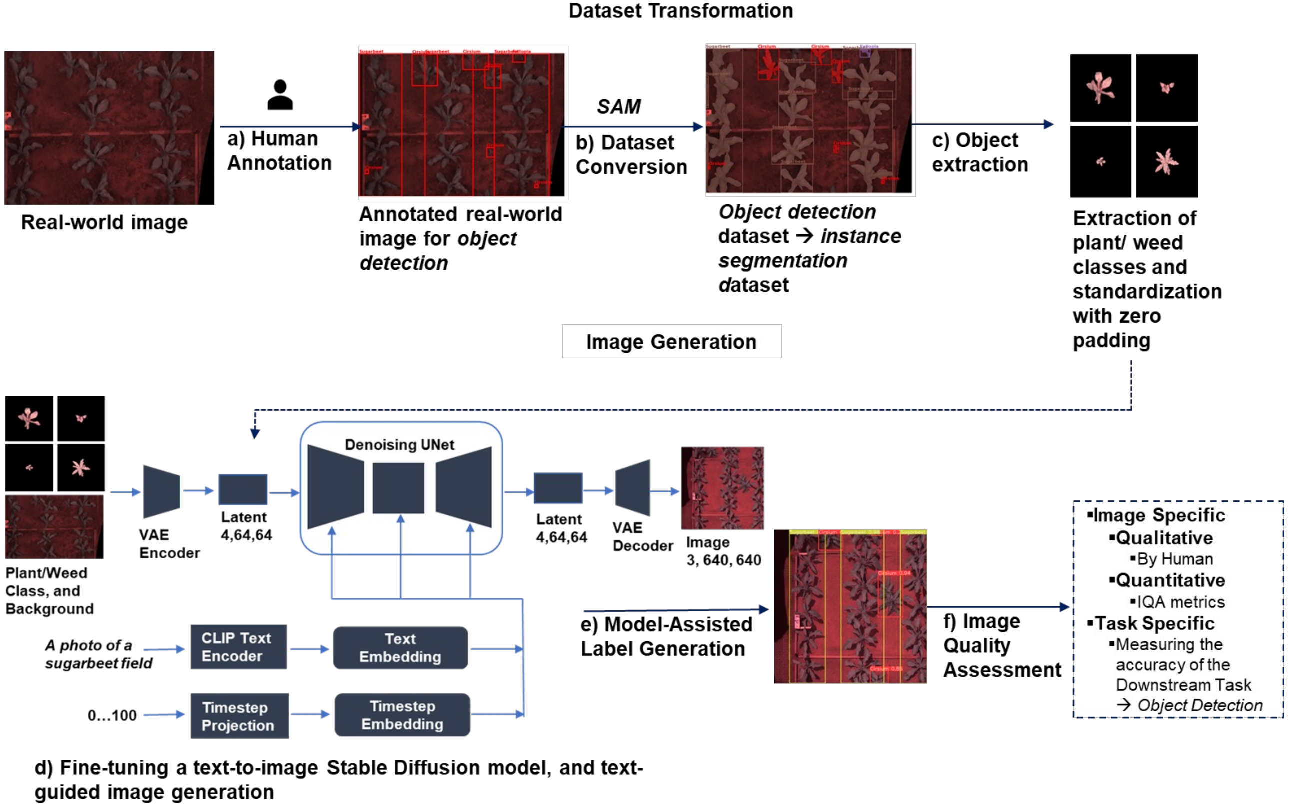
BOSCH

xarvio® Digital Farming Solutions powered by BASF

Actively associated: AMAZONE

IV. Resource-efficient AI for agricultural applications

GenAI-based training data creation



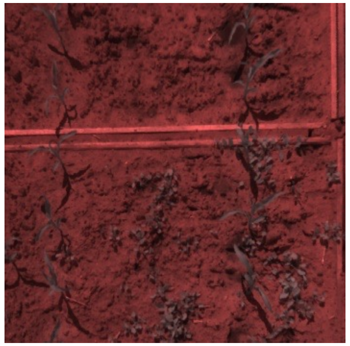
Modak, S., Stein, A. (2024). Synthesizing Training Data for Intelligent Weed Control Systems Using Generative AI. In: Architecture of Computing Systems. ARCS 2024. Lecture Notes in Computer Science, vol 14842. Springer, Cham. https://doi.org/10.1007/978-3-031-66146-4_8

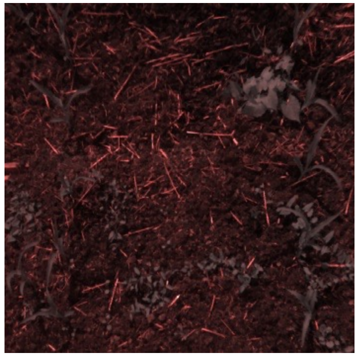
Modak, S., Stein, A. (2024) Enhancing weed detection performance by means of GenAI-based image augmentation. In: Proceedings of Computer Vision and Plant Phenotyping (CVPPA) Workshop, ECCV Workshops, to appear, Springer, Preprint: http://arxiv.org/abs/2411.18513

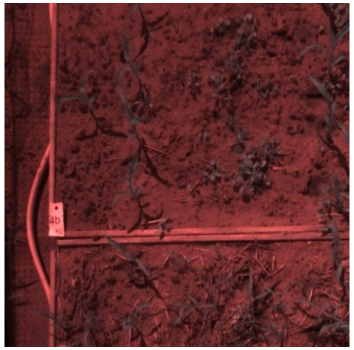
IV. Resource-efficient AI for agricultural applications

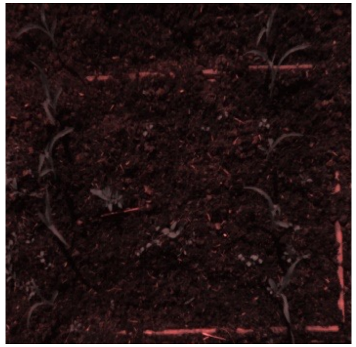
GenAI-based training data creation

Real-world Images

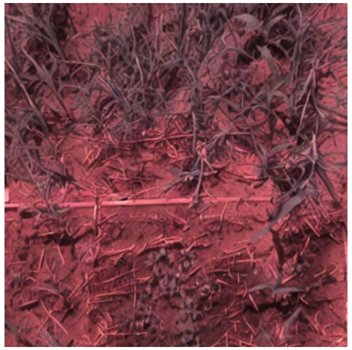


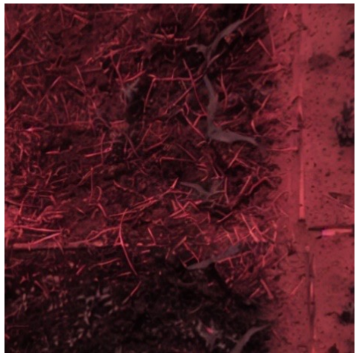


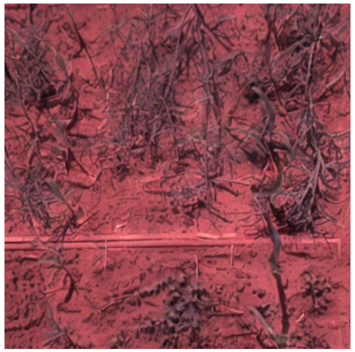


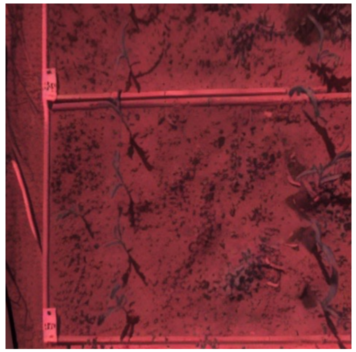


Synthetic Images

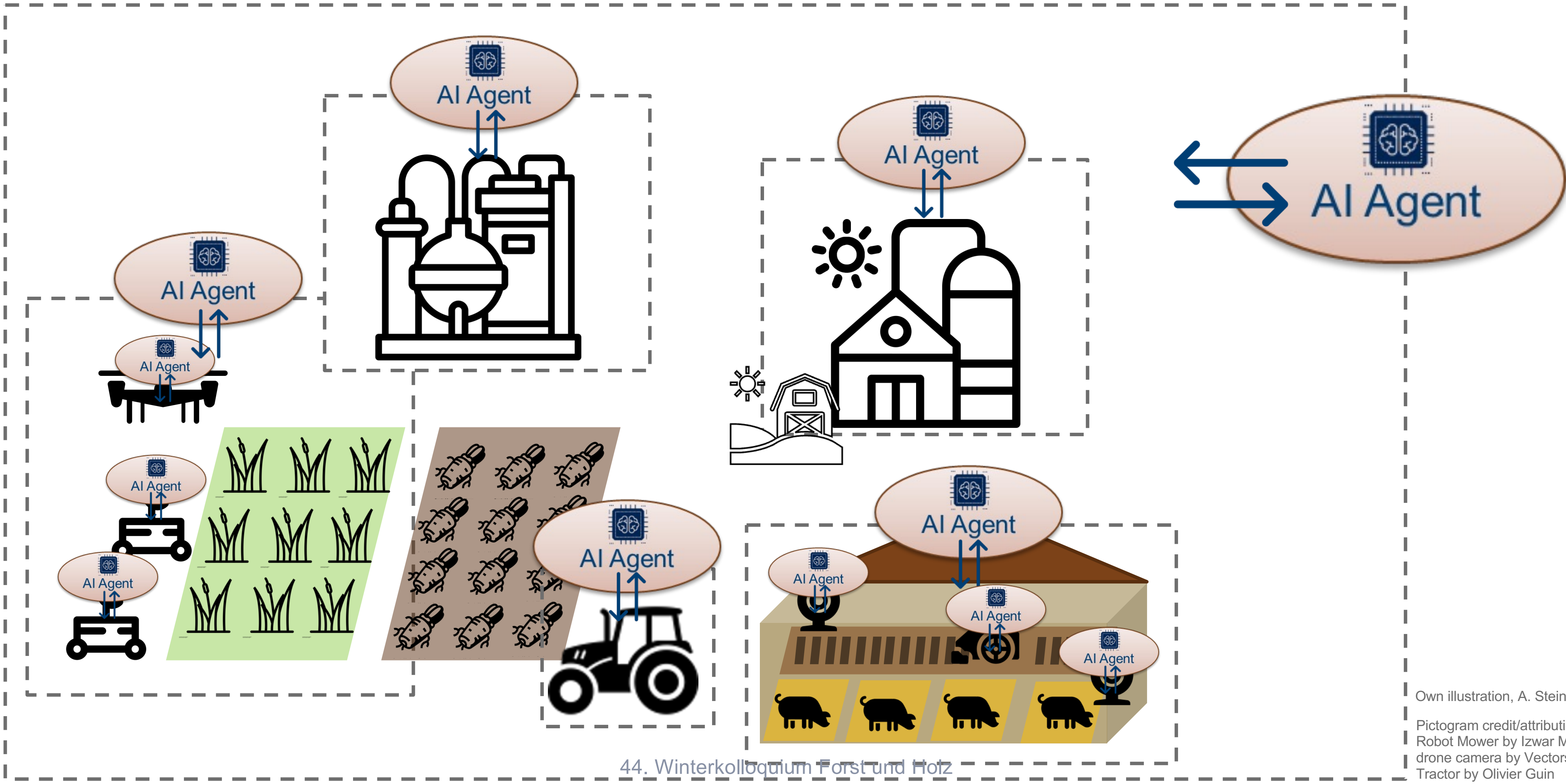






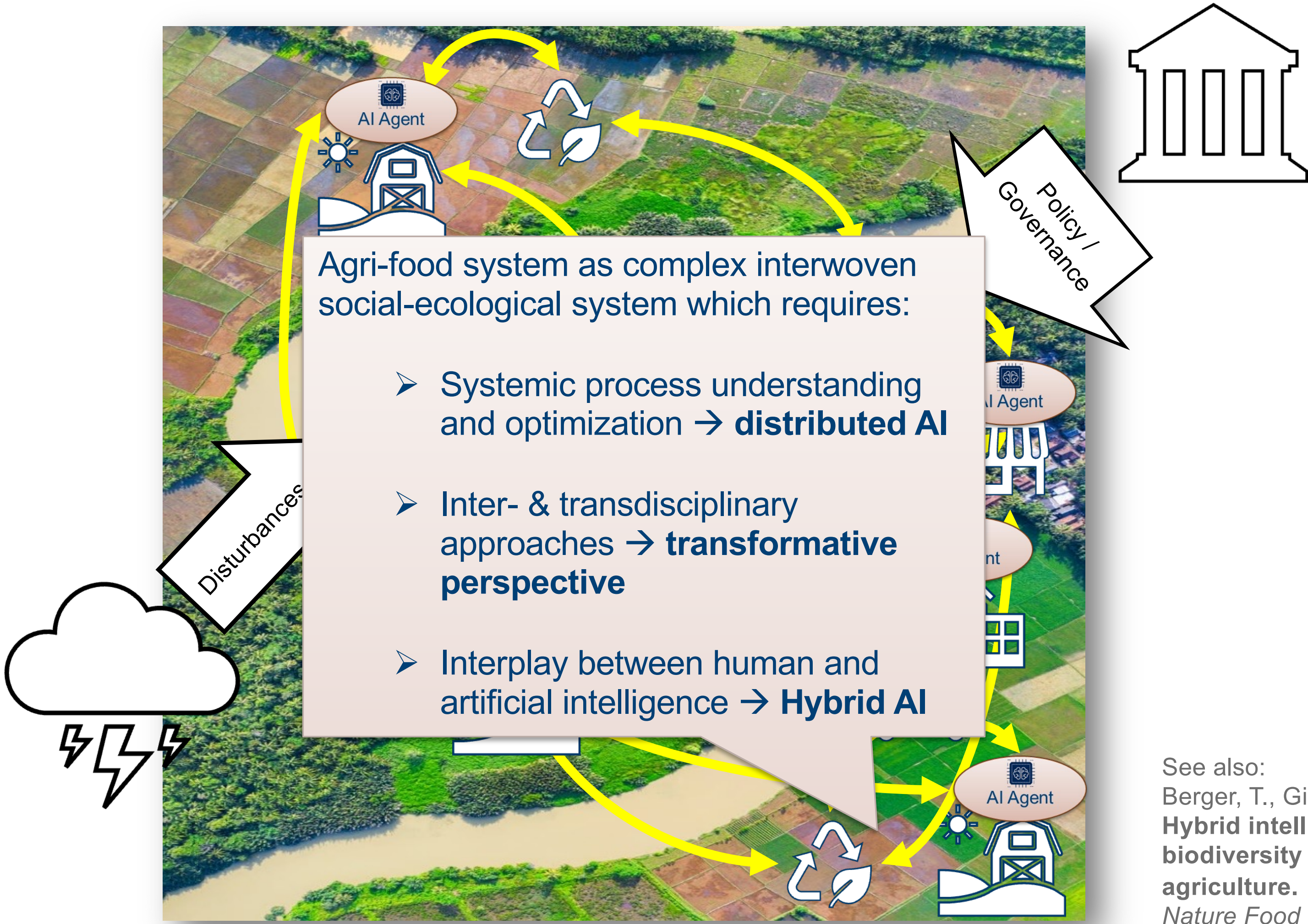


Thought experiment



Own illustration, A. Stein

Pictogram credit/attribution:
Robot Mower by Izwar Muis
drone camera by Vectors Market
Tractor by Olivier Guin
from NounProject.com



Agri-food system as complex interwoven social-ecological system which requires:

- Systemic process understanding and optimization → **distributed AI**
- Inter- & transdisciplinary approaches → **transformative perspective**
- Interplay between human and artificial intelligence → **Hybrid AI**

See also:
Berger, T., Gimpel, H., Stein, A. *et al.* **Hybrid intelligence for reconciling biodiversity and productivity in agriculture.** *Nature Food* **5**, 270–272 (2024)

Own illustration, A. Stein
Landschaftsaufnahme: frei verfügbar über pexels.com

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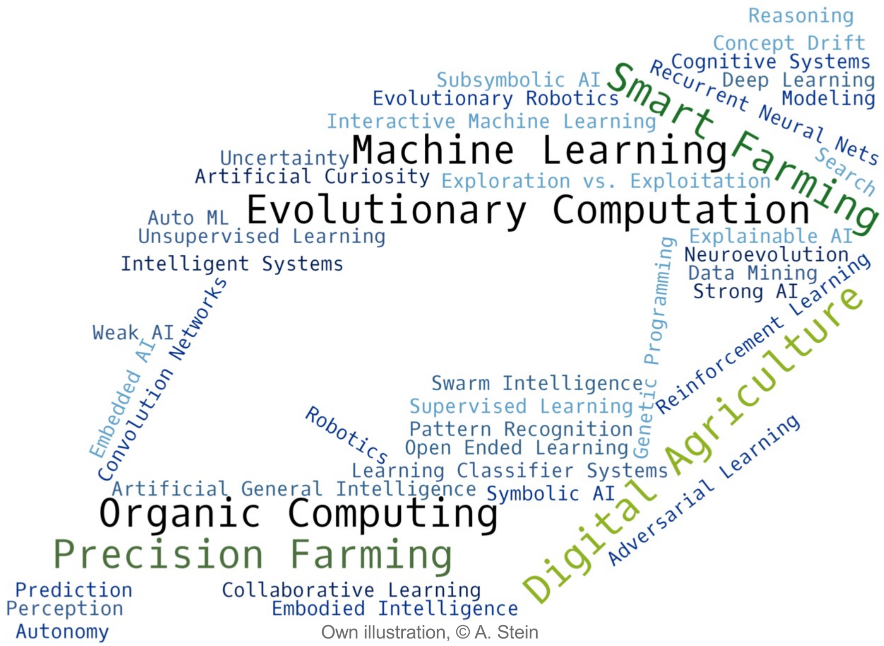
- Tomorrow: Research activities
- **Aspects of getting there**



Own illustration, © A. Stein

Systemic view on agriculture

… next to a purely technological angle
(following Ryan et al. 2023)

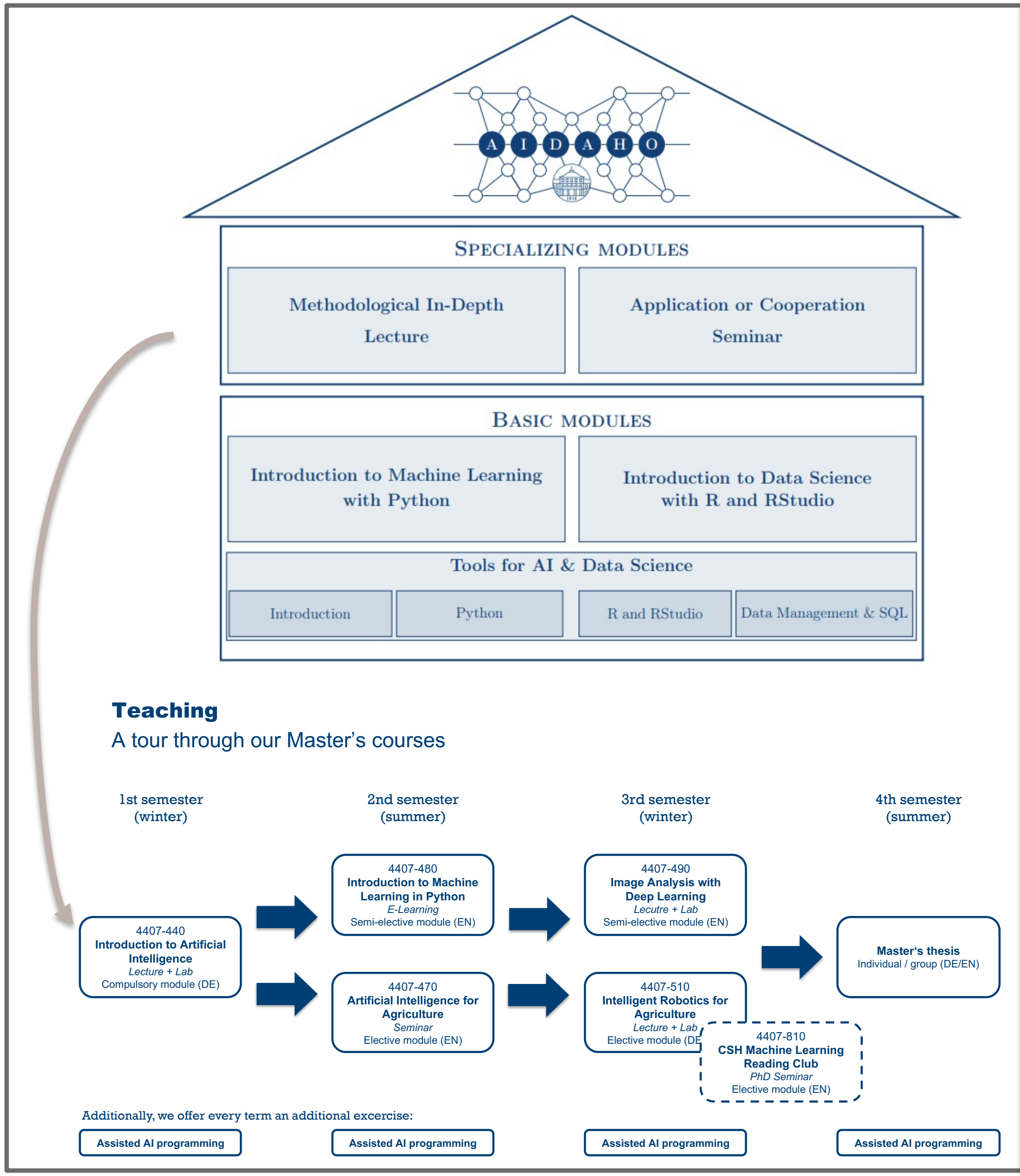
Own illustration

- Agriculture as a **social-ecological system**
- Technological innovations need **financially feasible** solutions to be adopted
- Next to technological aspects, **further dimensions** matter
  - Socio-political conditions, e.g., subsidies, acceptance
  - Environmental boundaries, e.g., Biodiversity, soil degradation
  - Ethical concerns, e.g., risk for digital divide

➢ **Transdisciplinary** approach deemed key for successful technology adoption and potential realization

Digital agriculture in education

- Educate in **digital competences**
  - Bring next gen. famers closer to possibilities of digital technologies
  - ➢ Increase trust in digital technologies, e.g., AI
- Strengthen **data literacy**
  - Data management, security, privacy
  - But: No need to become `data scientists’
  - ➢ Lower reservation, increase data sovereignty
- Create **readiness** to **self-assess suitability** of new digital tools
  - … with their **potentials**, **challenges** and **risks**
  - ➢ Better basis for **farm-individual adoption decisions**



Some activities at University of Hohenheim

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Summary

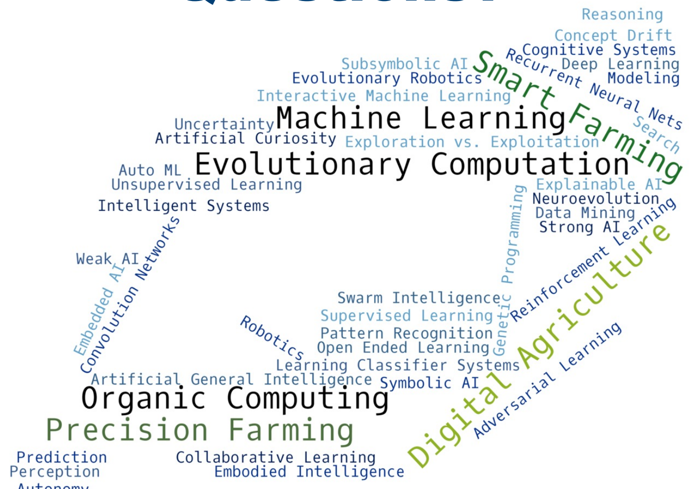
Is AI a gamechanger in agriculture as of today?

- **Agricultural AI applications** in place
  - Research spans all agricultural sectors
  - First commercial solutions using **isolated AI technology** to increase automatization
  - **But**: Much R&D ahead to leverage AI's full potential

- **Systems thinking:** Beyond isolated AI techniques
  - Untapped potential
  - Integrating well-designed AI agents into **Intelligent AgTech systems**
  - Connecting these AI-based systems across the **technological scales of digital agriculture**

- **Further aspects** of *changing the game*
  - Education: Early training of digital competences
  - Transdisciplinary research: Actively involve actors

Questions?



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