Glimpses of an agri-tech future –
from 3 decades on the precision agriculture adoption path

Is robotic farming the next wave of agricultural innovation? https://www.agxeed.com/our-solutions/agbot-2-055w4/

Handheld smart phone based plant sensors may make precision farming profitable for small and medium farmers - https://yarairix.com/fr/ntester-clip

Drones may be more useful for VRT spot spraying, than for data collection - https://www.marketreportgazette.com/2019/

Prof. James Lowenberg-DeBoer
Elizabeth Creak Chair of Agri-Tech Applied Economics
Harper Adams University

Global Institute for Agri-Tech Economics

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Just in case you are wondering about Harper Adams University:

- Harper Adams is a British public agricultural research and teaching university established in 1901
- 150 miles northwest of London in Shropshire
- Harper Adams has over 5000 students, all in agriculture.
- Campus within a 1200 acre working farm

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Claim to fame - Harper Hands Free Farm has been growing crops autonomously since 2016

Wheat, barley and field beans grown from seeding to harvest with retro-fitted conventional equipment

Hands Free Farm retro-fitted small conventional equipment to test the swarm robot hypothesis.

Source: https://www.handsfree.farm/images.html

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Goals of this presentation:

1) Reminder on current status of precision ag adoption.
2) What have we learned about PA adoption trends?
3) Look into the future of precision agriculture, autonomy and general agri-tech adoption trends.

Agrointelli Robotti as part of a strip cropping trial at Wageningen University. Researchers are asking what new production practices are practical and profitable with advances in technology?

Photo source: https://www.wur.nl/en/product/robotti-1.htm

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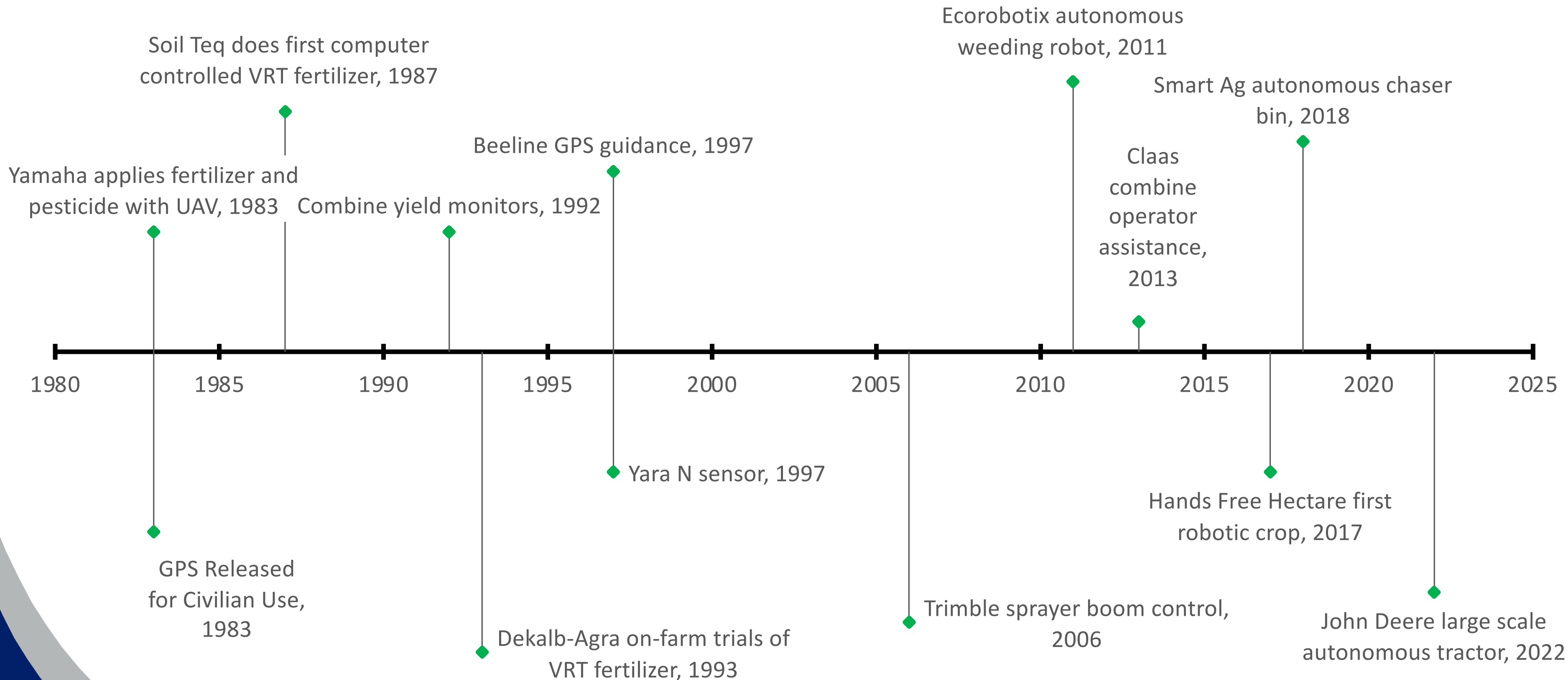
Some Precision Agriculture Milestones



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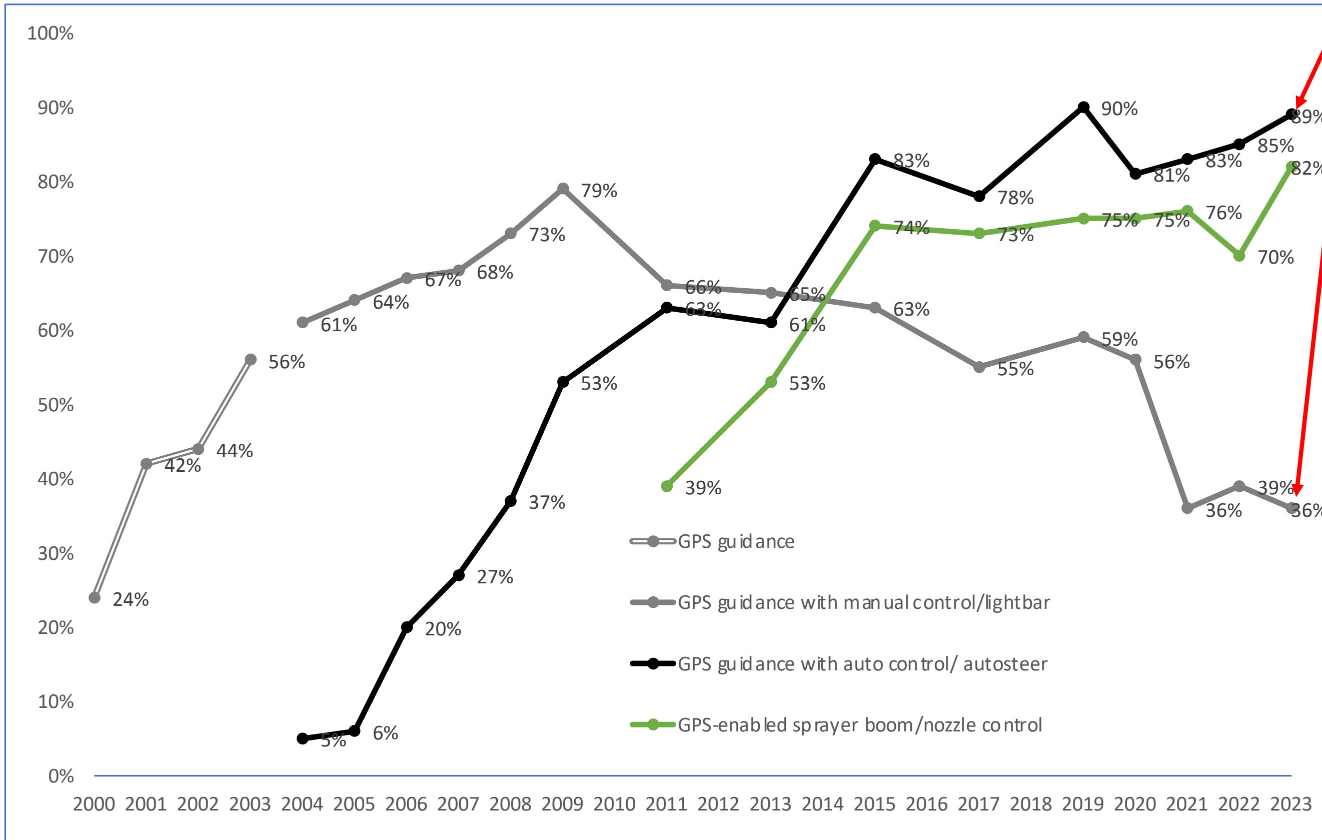
USA Ag Retailer Use of GPS Guidance

In 2023, 93% of ag retailers use either lightbars or autosteer.

- Global Positioning System (GPS) was the first Global Navigation Satellite System (GNSS).
- GPS lightbars rapidly adopted starting in late 1990s and then replaced by autosteer.
- Autosteer rapidly adopted starting in about 2004.
- Both are easy to use and have short run benefits



Source: Erickson and Lowenberg-DeBoer, 2023 – https://www.croplife.com/management/precision-survey-ag-dealers-respond-to-marketplace-shifts/

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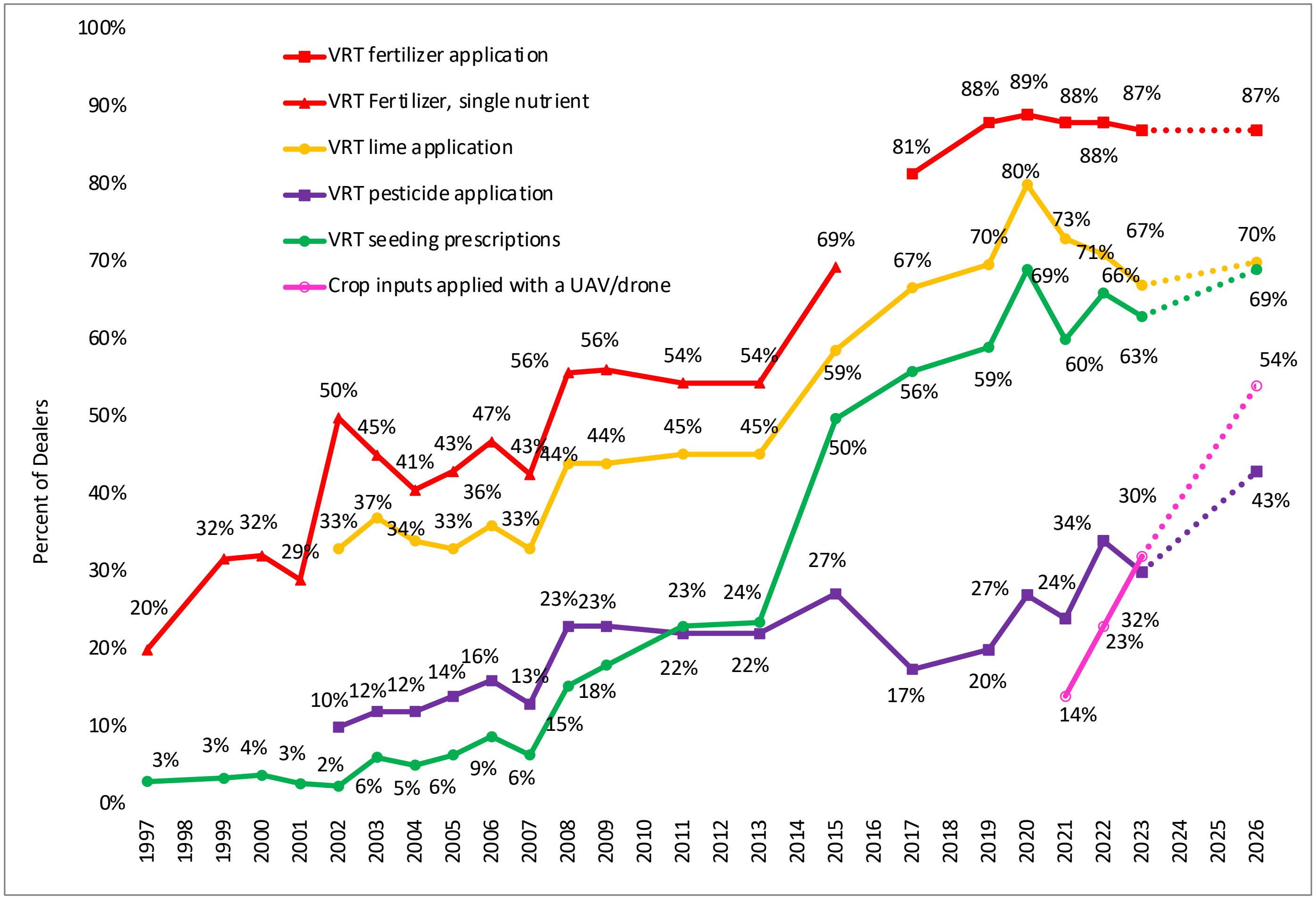
Dealer Adoption of Variable Rate Technology (VRT), % of respondents

- VRT fertilizer was introduced in the USA in the early 1990s.
- Fertilizer dealers moved quickly to provide VRT fertilizer services.
- VRT pesticide services have languished, mostly because annual weeds, insects and plant diseases are difficult and costly to map.
- VRT seeding is done by some farmers, but dealers sometimes help with prescription maps.



Source: Erickson and Lowenberg-DeBoer, 2023 – https://www.croplife.com/management/precision-survey-ag-dealers-respond-to-marketplace-shifts/

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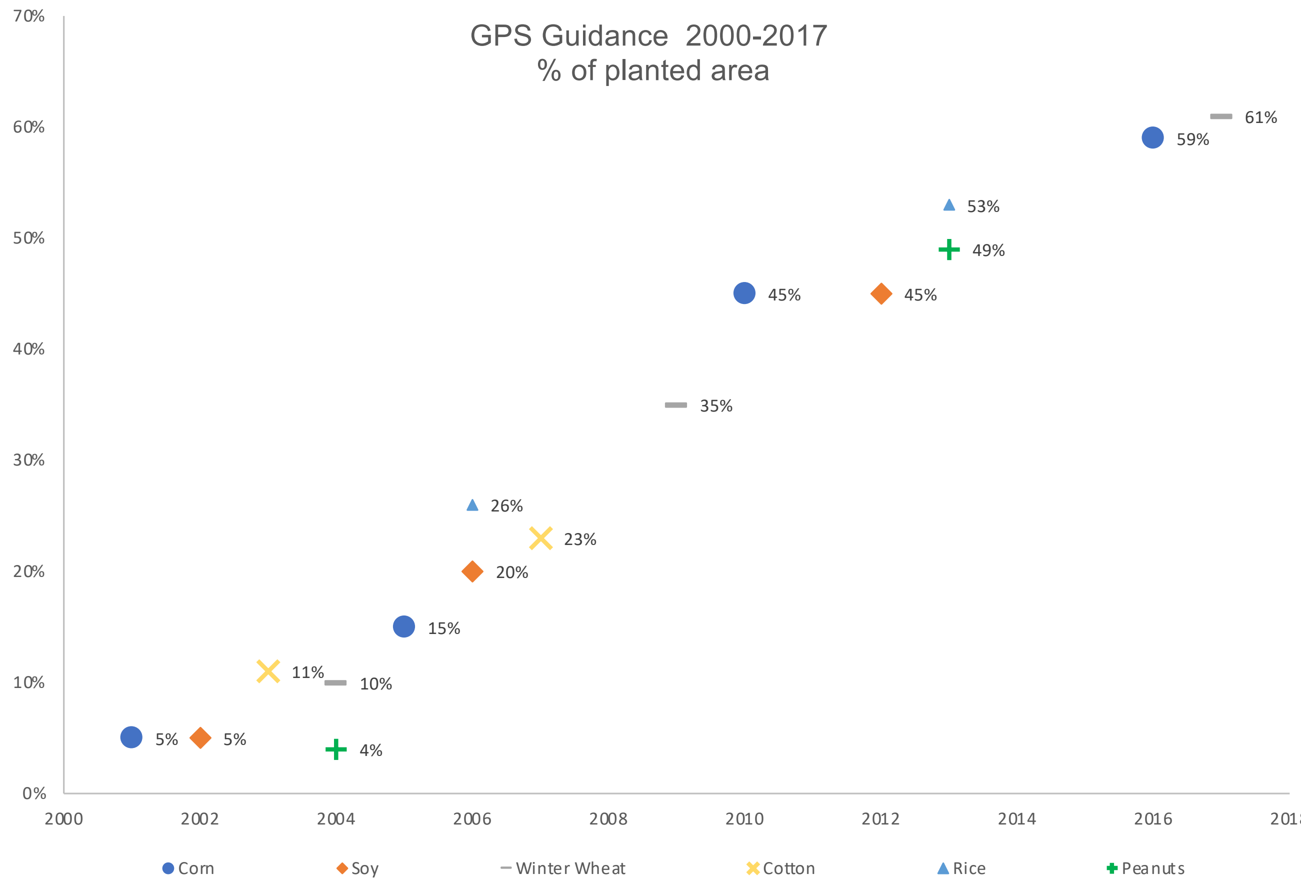
Farmer Adoption of Global Navigation Satellite Systems (GNSS) Guidance in the USA

- USDA ARMS data has an irregular survey cycle with different crops each year.
- Easy to imagine that the cloud of data points forms a classic “S” shaped adoption curve for GNSS guidance
- Other data suggests that sprayer boom control, seeder row shut offs and other GNSS guidance related technology has been adopted rapidly by farmers as well as dealers.



Source: Based on data from USDA ARMS - https://data.ers.usda.gov/reports.aspx?ID=17883

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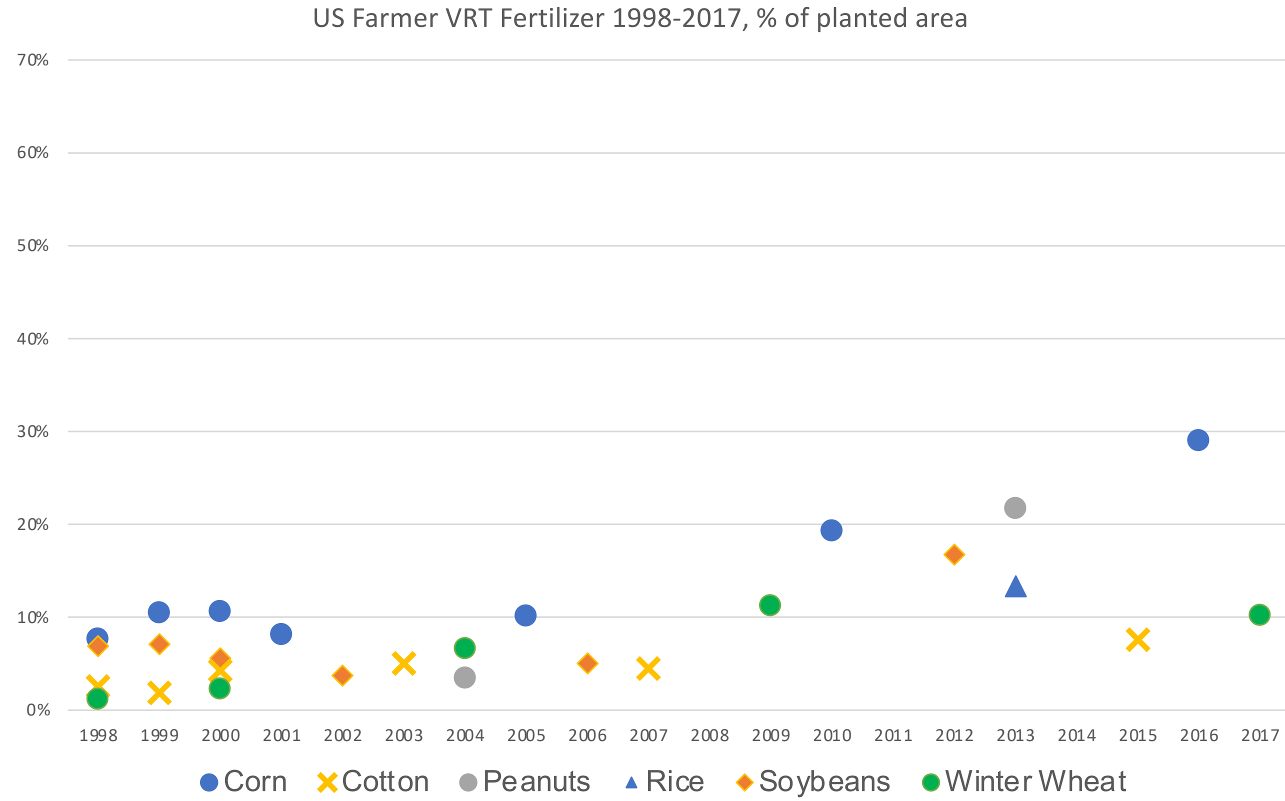
US Farmer Adoption of Variable Rate Technology (VRT)

- Farmer use of VRT fertilizer on cereals and oilseeds rarely exceeds 30%
- In spite of widespread availability of VRT services, intense publicity, and subsidies in some counties and states, VRT use by US farmers shows only a slight upward trend.
- The >20% adoption of VRT in the 2010-12 period was during a period of high grain prices.



Source: Based on data from USDA ARMS - https://data.ers.usda.gov/reports.aspx?ID=17883 and Schimmelpfennig and Lowenberg-DeBoer, 2020.

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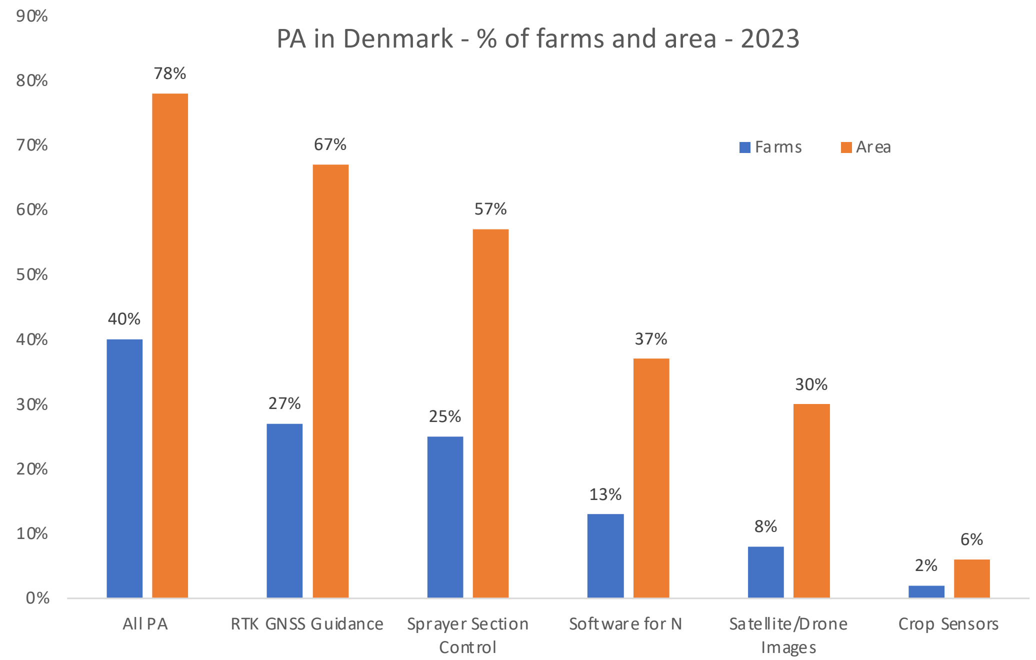
Precision Agriculture in Denmark

- Denmark Statistics does a PA survey of all Danish farms growing crops.
- Adoption pattern similar to US:
  - Guidance most common PA technology.
  - More PA on larger farms
  - VRT fertilizer adoption modest - In 2017, VRT used by 7% of farms. VRT not reported in recent surveys.



Source: Denmark Statistics, 2023

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Agri-tech pipeline: Robots are starting to appear in fields

- Weeding robots are being trialled all over Europe led by France, where roughly 600 robots are being used for mechanical weeding of vegetable and sugar beet crops in 2023.
- The worldwide agricultural robots market was estimated at US$13.4 billion in 2023.
- An estimated 250 companies worldwide are developing crop robots.
- The 2023 FutureFarming crop robot catalogue (https://www.futurefarming.com/dossier/field-robots/) has 60 robots being marketed by 50 medium and small manufacturers, plus two companies with tractors that can be operated autonomously and 6 companies with retrofit kits to convert conventional tractors for autonomous use.
- In North America John Deere and CNH are commercializing autonomous crop equipment.

Robotti, weeding robot, weeding French beans on Sandfield Farm, Stratford on Avon, UK, 25 June 2021

Source: James Lowenberg-DeBoer

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2022 CROP ROBOTICS LANDSCAPE

The Mixing Bowl · Better Food Ventures

AUTONOMOUS MOVEMENT | **CROP MANAGEMENT** | **HARVEST**

ROW CROP · SPECIALTY FIELD · ORCHARD-VINEYARD · INDOOR

Navigation/ Autonomy
AgriRobot, Cognitive Pilot, Trimble, Sabanto, CHCNAV, FJDynamics, ASI, Steyr, Cerea, GPX Solutions BV, Topcon, Ag Leader, Blue White Robotics, Agtonomy, GOtrack, Braun, Robo Tech, Singular XYZ

Small Tractor/ Platform
Saga 247, Kubota, Donkey, AI.Land, The FarmHand Tractor, Elatec, Z Tractor, farm-ng, Sabi Agri, Korechi, Continental, Monarch, Future Acres, Exobotic, Greenculture, Burro, Vinergy, XAG, Exxact Robotics, Raussendorf, digital workbench

Indoor Platform
Seasony, Automato Robotics

Large Tractor
Nexat, John Deere, AGXEED, Raven, AgroIntelli, autoagri, Bear Flag Robotics, iOX, Amos, Tarra, New Holland, SITIA, oxin, Slopehelper, ViTiBOT

Scouting
EarthSense, Egrobots, Meropy, Solinftec, Small Robot, sentera, Censys, AgEagle, quantum systems, draganfly, Delair, Atmos, wingtra, aerobots, Event 38, microdrones

Robotic solutions placed in other task/product categories on this landscape may have scouting capabilities in addition to their primary function.

Indoor Scouting
Gearbox, ecoation, Iunu, Corvus Drones, HortiKey

Preparation & Planting
Fendt, Horsch, Rowbot, Terraclear

Drone Application
AVision, Kray, precision.ai, Guardian Agriculture, Thanos, Formaro Robotics, TTA, Joyance, Nileworks, M-Drone, Pyka, Lahak, Drone Volt, Drone Agro, Marut Drones, Titan, hylio, dji, Fly Dragon, X-Drone, Hadyi, leadingedge, Brouav, Asta, hse, Aero41, Garuda Aerospace

Indoor Drone Protection
pats

Application
Case IH, Agrifac, Carbon Bee, Verdant Robotics, Bosch, Augmenta, DAT, Dammann, Bilberry, Amazone, Blue River, Claas, Plantium, Autonomous Pivot, Greeneye Technology, ecorobotix, Verdant Robotics, Saga Robotics, TRIC, Xmachines, Mechatronix, LJ Tech, Yanmar, Kilter, GUSS, Edete, Midnight Robotics, Jacto, INESCTEC, Free Green Nature

Indoor Application
polybee, AIS, Micothon, Ftek, Berg, Hada, arugga

Weeding & Thinning
rootwave, Kongskilde, HayBeeSee, Steketee, Farming Revolution, Nucrop, Vision Robotics, FarmDroid, Earth Rover, Stout, Carre, Dahlia Robotics, odd.bot, Carbon Robotics, F Poulsen Engineering, naïo, Farmhand Automation, Kult, FarmWise, Weedbot, Ekobot, garford, nexus, Tensorfield, Feldklasse, AgriBotix, Aigen, Ferrari, Ullmanna, Pixelfarming Robotics

Orchard-Vineyard Weeding & Pruning
Vitirover, Wall-ye, Aigro, InsightTrac, Beagle, Ladybug Robotics, Eleos, aigritec

Indoor Deleafing
Polariks, Saia, Octiva, Lenzeel

Specialty Field Harvesting
Muddy Machines, Lapalme Agtech, Harvest Croo Robotics, Kopppert Machines, advanced.farm, MiFood Robot, AVL Motion, Fieldwork Robotics

Orchard-Vineyard Harvesting
Tevel, OMC, Ripe Robotics, RoboticsPlus, UBot, Fine Field

Indoor Harvesting
Iron Ox, Tortuga AgTech, Four Growers, iFarm, Outback Robotics, Metomotion, Denso, Agrobot, certhon, Crux, Root AI, neupeak, Dogtooth, Organifarms, Mycionics, Xihelm

Companies appear only once, though some may offer multiple or multi-use robots; they are placed according to primary function. Some segments span multiple crop systems as solutions may be applicable across crops. Logo positions are not necessarily indicative of crop system applicability.

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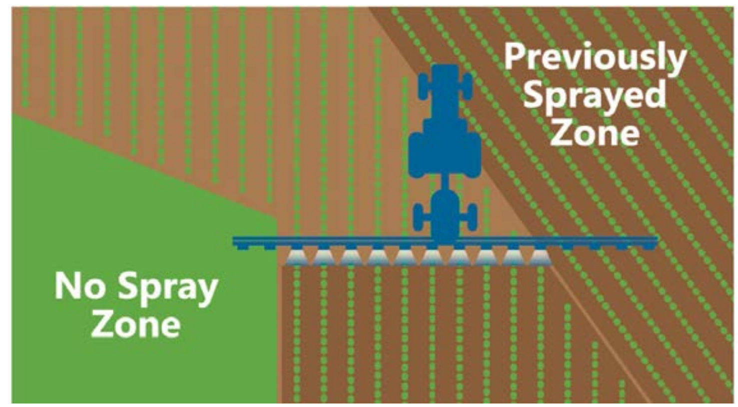
THE VINE

GNSS Guidance Success Story

- GNSS guidance being widely adopted on mechanized farms almost everywhere.
- Sprayer boom control, seed row shut offs and other technology linked to GPS guidance being widely adopted.
- Investment in GPS guidance and related technologies cashflowed by reduction in overlap and more efficient field operations. Other benefits (e.g. reduced fatigue, flexibility in hiring) are unquantified side effects.



GPS sprayer boom control reduces pesticide skip and overlap.

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The success of GPS guidance is not a surprise – we had clues in the late 1990s

- In 1998 with encouragement from Trimble and other companies, we did the first economic analysis of GNSS guidance.
- This analysis showed substantial gains from reducing skip and overlap in input application.
- Given ease of use, relatively low cost of trialling, and easily visible results we predicted quick and widespread adoption for GPS guidance.

Table 1. Cost and Benefit Examples for GPS Guidance and Foam Markers for Use by Producers.

Item	Foam Marker	GPS Guidance	Lightbar Only
Costs:			
Purchase Price, $	$1000	$7000	$3000
Useful Life, years	5	3	3
Annualized Cost, $.yr	$264	$2815	$1206
Recurring Cost:			
Foam, $/yr	$336	0	0
Differential			
Correction, $/yr	0	$800	0
Annual Cost, $/yr	$600	$3615	$1206
Annual Cost, $/a/yr	$0.20	$1.20	$0.40
Benefits in Reducing Overlap:			
Percent of Area Overlapped	10%	5%	5%
Overlap Acres	300	150	150
Opportunity Cost Sprayer Operation			
$/a	$4.40	$4.40	$4.40
$/yr	$1320	$660	$660
Extra Chemical and Fertilizer, $.yr	$3000	$1500	$1500
Overlap Cost, $/yr	$4320	$2160	$2160
Overlap Cost, $/a/yr	$1.44	$0.72	$0.72
GPS Net Benefit		-$0.29	$0.52

Source: Lowenberg-DeBoer (Purdue Agricultural Economics Report, 1999)

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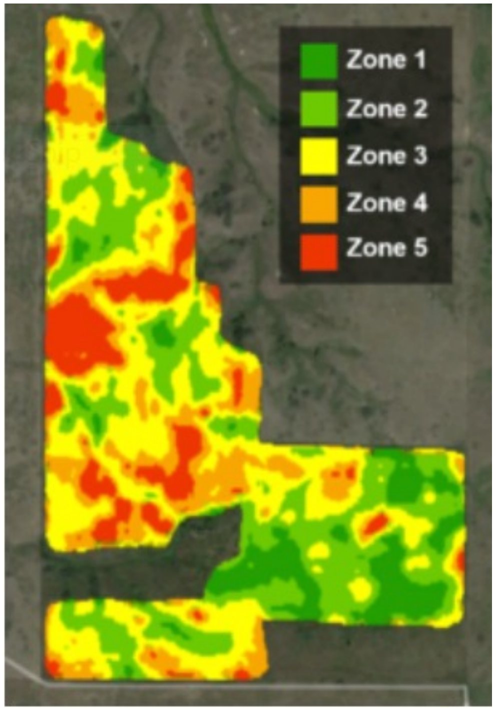
Variable Rate Technology Adoption has Lagged

- Variable Rate Technology (VRT) being adopted in niches where it is highly profitable, but VRT adoption for all broad acre crops only rarely exceeds 20% of area or farms.
- Constraints to VRT adoption include:
  - High cost of site specific information (e.g. grid or zone soil sampling)
  - Cost of developing individualized prescription maps
  - Lack of demonstrated value – impact on yields and profits often hard to see
  - Cost of being wrong (and over applying) is often small because environmental impacts not measured



https://www.agvise.com/zone-soil-sampling-and-variable-rate-fertilization-optimizing-profits/

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The earliest VRT fertilizer trials generated adoption concerns

- From the beginning on-farm VRT fertilizer trials showed mixed results profitable some years and not others.
- The early trials also showed implementation challenges in soil testing, creating recommendation maps, and spreading accuracy.
- Based on mixed profitability and implementation issues adoption challenges were predicted in the mid1990s.

Table 2. Crop and net return by farm and year for on-farm trials of variable rate P and K

Year and farm no.	Crop	Net returns by treatment		
		Whole field	Grid	Soil type
		$/acre		
1993				
2	Corn	311.61	281.36	244.13
4	Corn	141.21	128.65	157.20
5	Corn	153.78	93.14	187.72
1994				
1	Wheat	110.19	136.20	120.39
2	Soybeans	164.73	140.78	139.96
3	Soybeans	216.52	202.57	149.83
3	Wheat	100.76	95.37	87.66
4	Soybeans	211.98	114.68	205.89
6	Corn	141.45	186.98	196.76
1995				
1	Corn	193.70	206.98	177.72
2	Corn	64.91	122.24	130.04
6	Soybeans	96.91	116.60	142.48

Some of the first variable rate fertilizer trials using GPS and yield monitors were done in Dekalb County, Indiana (Source: Lowenberg-DeBoer and Aghib, 1999)

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What have we learned about PA adoption?

- The best single predictor of long term adoption is benefits to the farmer.
- The time path to adoption is highly variable and depends on many factors, including:
  - Marketing
  - Education of farmers
  - Social pressure
  - Regulation

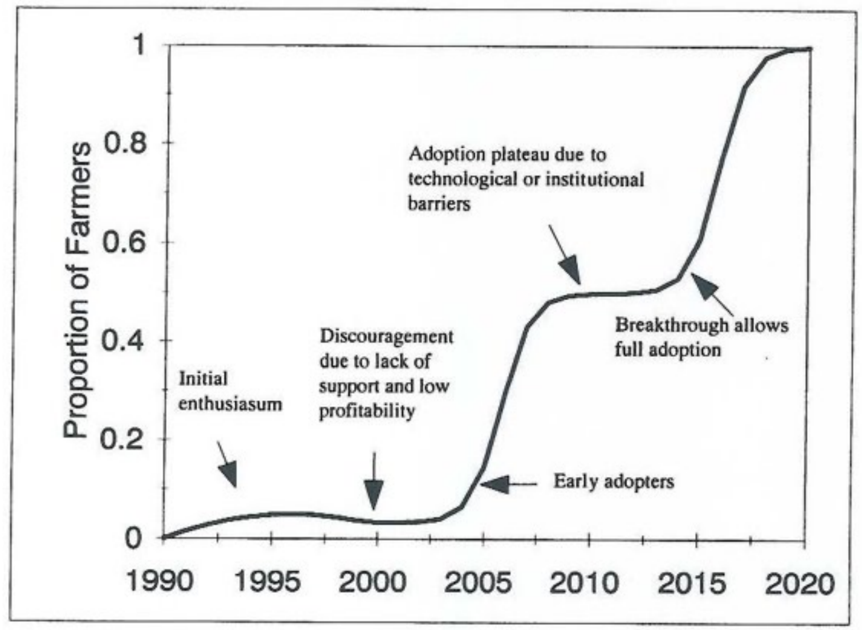

Figure 7. An alternative adoption scenario for integrated precision farming systems using information technology for spatial and temporal management multiple inputs.

Source: Lowenberg-DeBoer, SAE, 1998

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Adoption potential of PA technology in the pipeline?

Machine vision targeted herbicide:

- Potentially quite profitable for farmers.
- Adapts easily within conventional farming systems.
- Responds to public sentiment and regulatory pressure to reduce herbicide use.
- In the longer run it shifts plant protection business toward a service model, away from sell quantity.

John Deere See & Spray enables herbicide application among maize, soybean and cotton plants.

https://www.deere.com/en/news/all-news/see-spray-ultimate/

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Mechanical weeding for commodity crops

- Automated mechanical weeding is currently economically competitive for wide row high value organic crops (e.g. sugar beets, vegetables, flowers).
- Currently automated mechanical weeding is commercialized with human operators or autonomous.
- Without a major technologically advance, mechanical weeding will be profitable for grains, oilseeds and other commodity crops only if done autonomously and probably with machine vision to allow weeding closer to crop plants.

Mechanical weeding with autonomous crop equipment could make farms more profitable and reduce the environmental footprint of agriculture. (Source: https://farmdroid.dk/en/product/)

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Combine AI Operator Assistance Technology

- Potentially grain savings of 3-7 bu./a
- Integrates with current harvest technology.
- Currently only available as OEM equipment only on the largest combines.
- Currently focus on physical parameters (e.g. grain loss, grain quality, fuel use).
- Future decision support to incorporate grain prices, fuel costs and time availability.

Farmwave AI uses cameras on the combine to monitor harvest grain losses
https://www.youtube.com/watch?v=VSmHEtnKHnY

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Co-robotic large machine automation

- Co-robotic technology is being commercialized for large farm machines.
- Having a human operator in the field reduces safety concerns around large autonomous machines.
- Co-robotics for large, well capitalized farms fits the business model of major manufacturers.

A "leader-follower" multi-tractor tractor system helps leverage the time of the operator in the field by allowing them to supervise the work of multiple machine.

Source: http://gardsdrift.no/traktorer-%C3%A9n-sj%C3%A5f%C3%B8r

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For example co-robotics for seeding

- John Deere introduced an autonomous R8 in 2023 for the US and Canada.
- In theory the R8 can work without in-field human supervision and that is legal in most of USA and Canada.
- My hypothesis is that it will be initially used co-robotically, for instance to prepare a seedbed in the same field as a human driven planter tractor.

https://www.deere.com/en/autonomous/

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Swarm robotics would be a paradigm change

- When human drivers are removed the economic drive to use large machines almost vanishes.
- Swarm robotics potentially cuts both labour and capital costs.
- Farming with many small autonomous machines radically changes the economies of size in agriculture.
- Because a shift to swarm robotics would involve major changes in farm size, organization and management, it may take some time.

Many researchers envision swarms of small robots, instead of large machines – Pedersen, Fountas and Blackmore, 2008

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"Why the low adoption of robotics in the farms?"

- That premature question is from the title of Gil et al. (*Smart Agricultural Technology*, 2023).
- A better question would be why companies have been slow to commercialize ag robots?
- Some hypotheses include:
  - Engineering challenges – still exist for horticulture and for swarm robot coordination.
  - Business model – swarm robotics do not fit the large scale agribusiness model.
  - Regulatory issues – e.g. in field human supervision rules, liability issues.

Smart Ag started selling autonomous chasers bins in 2019. Several companies now offer this co-robotic technology.

https://www.oemoffhighway.com/trends/gps-automation/news/21020794/smart-ag-unveils-autocart-driverless-tractor-technology-at-2018-farm-progress-show

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UK crop robot code of practice

One of the key constraints on adoption of autonomous crop machines are regulatory and liability questions.

The US state of California has very tight regulations requiring on-site supervision of crop robots and limiting speed.

The EU Machinery Directive is being revised to make regulation of crop robots more flexible.

UK is several steps ahead because it has a voluntary crop robot code of practice.

BS 8646:2023

Use of autonomous mobile machinery in agriculture and horticulture – Code of practice

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Agri-tech further up the pipeline:

- Digital twins and AI optimization – decision support systems that use computer model to predict the performance.
- Agri-tech for regenerative agriculture:
  - Autonomous machines reduce the labour needed for mixed cropping.
  - Digital twins and AI can ease the decision making burden
- Alternative power for agriculture

Prairie strips are a form of regenerative mixed cropping drawing attention in North America.
https://www.nrem.iastate.edu/research/STRIPS/content/what-are-prairie-strips

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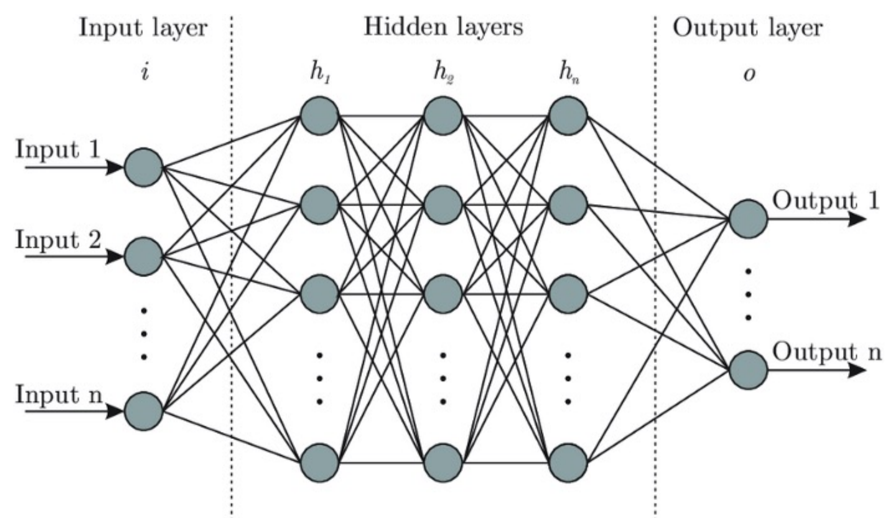
Digital twins and AI optimization

- AI optimization of cropping system digital twins is proposed to manage complex agricultural systems.
- Can accommodate thousands of variables and interations.
- Could identify potentially useful patterns and synergies.
- Succeptible to “hallucinations”.
- Very difficult at this point to determine the reliability of results



https://towardsdatascience.com/designing-your-neural-networks-a5e4617027ed

Neural networks are designed to mimic the function of the human brain

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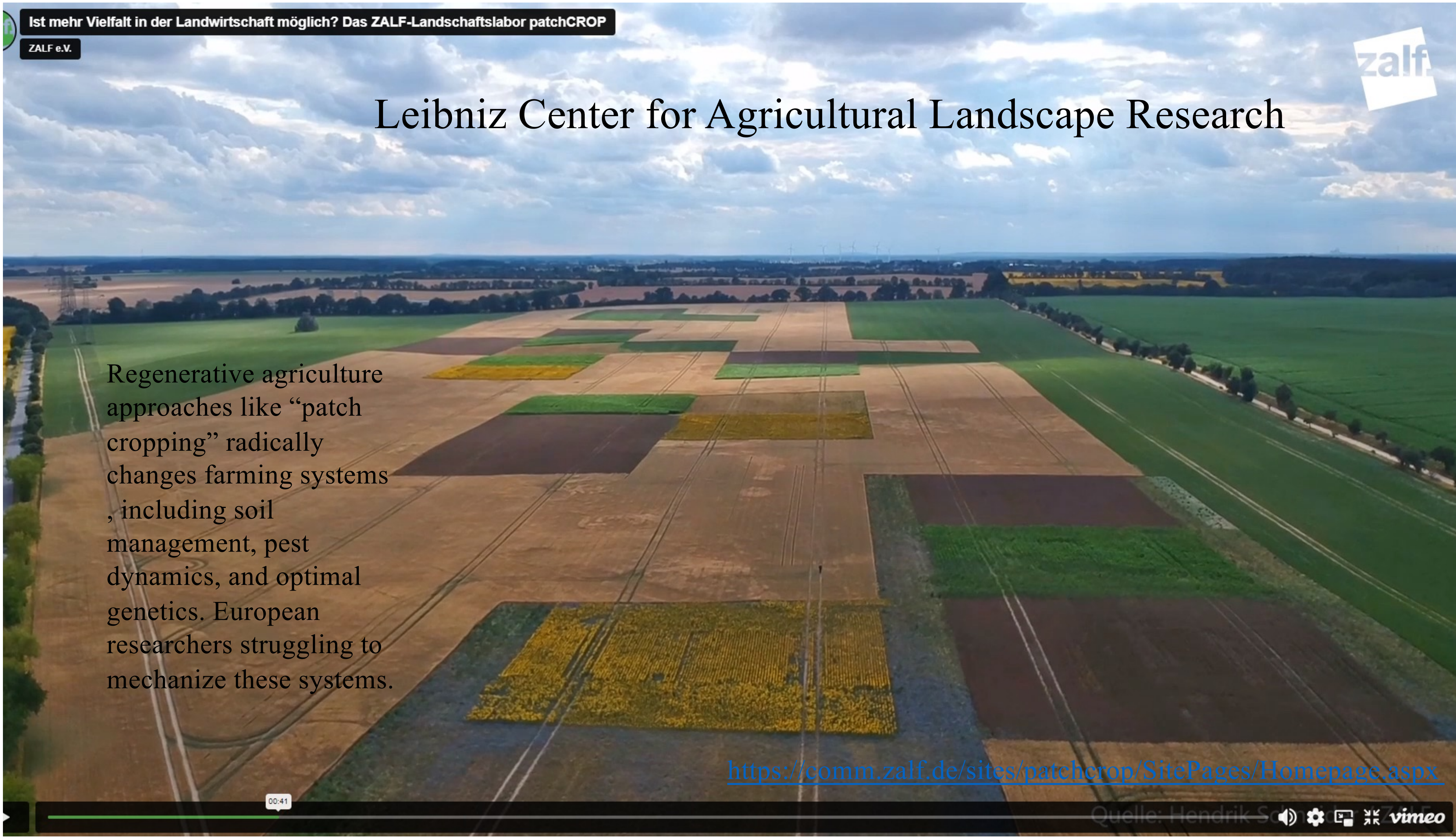
Leibniz Center for Agricultural Landscape Research



Regenerative agriculture approaches like “patch cropping” radically changes farming systems , including soil management, pest dynamics, and optimal genetics. European researchers struggling to mechanize these systems.

https://comm.zalf.de/sites/patchcrop/SitePages/Homepage.aspx

Alternative power sources for agriculture

- With current technology hydrogen power has many advantages for North American farms with large fields.
- For European farmers with small irregularly shaped fields, with many non-farm neighbors and doing protected agriculture (i.e. in greenhouses or polytunnels), battery electric has advantages.
- Methane, renewable diesel and other options.

https://fuelcellsworks.com/news/first-100-hydrogen-eox-electric-tractor-sold-by-h2trac/

The EOX-175 is 175 hp electric powered tractor with a hydrogen range extender manufactured in the Netherlands. With guidance, adjustable track width and four wheel drive it is especially designed for controlled traffic farming (CTF).

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Battery electric has a low power density and so it would mean changing how farming is done

- Current farming practices a designed for abundant, relatively low cost mobile power.
- Autonomy and electric power a logical combination.
- Punch (or dibble) planting would reduce draft power needed for planting.
- Alternatives already exist for electric powered spraying and weed control.
- Combines require large amounts of mobile power for threshing on the go. Electrically powered harvest may mean rethinking how harvest is done.

The 22 hp Farmtrac FT25G Electric tractor is the best selling electric tractor in the UK. It costs about US$30,000.
https://www.terryharrisonmachinery.co.uk/product/farmtrac-ft25g-electric-tractor/

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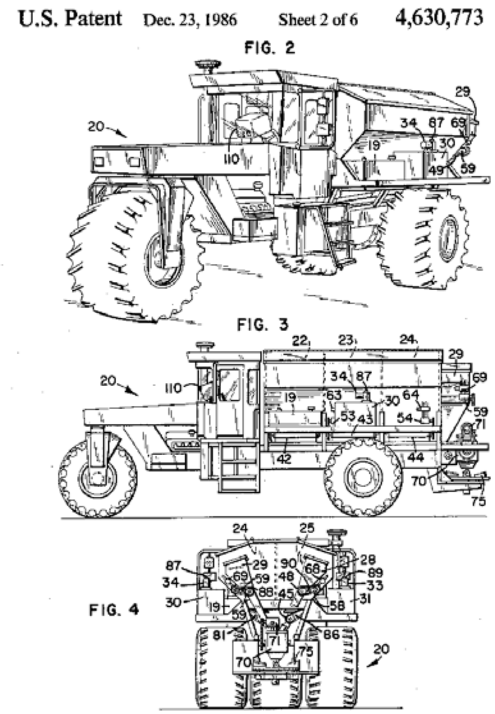
Take home messages:

- Achieving widespread adoption of agri-tech innovations requires great technology that fits the physical and social environment, and:
  - ❑Effective business models for manufacturing, distribution and use of that technology.
  - ❑Conducive regulatory framework
  - ❑Time
- Approximating long run adoption levels can be based
  - Farm level benefits (e.g. profits, labour flexibility)
  - Physical, financial and social constraints
- Predicting short run adoption patterns is very difficult and not needed for most strategic planning and public policy.



Soil TEQ applied for a patent on multi-product variable rate fertilizer spreader in 1986. That idea is still in the process of being adopted.

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