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Map on value-chain level impacts of NBS across scenarios

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Authors	Anke Möhring (FiBL), Christian Grovermann (FiBL), Anastasios Chatzigeorgiou (FiBL), Adrian Müller (FiBL), Mette Vestergaard Odgaard (AU), Morten Graversgaard (AU), Anton Rasmussen (ICOEL), Morten Winther Vestenaa (ICOEL), Pia Strunge Folkmann (Klimafonden Skive), Tommy Dalgaard (AU), Simon Willcock (University of Reading)
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1 Preface

Deliverable D4.3 assesses what changes a green biorefinery value chain would bring to the catchment of the Limfjord in Denmark. It is primarily intended to answer the following questions: how fast would farmers adopt the alternative cropping practice, who would supply the processors with biomass, at what cost to the public sector, and how large would the contribution be to the nitrogen reduction required of the region?

The assessment uses ADAPtES, a spatially explicit agent-based model in which farmers decide field by field whether to replace their crop rotation with grass-clover (Möhring et al., 2025). Processing agents decide whether and where facilities are established, based on available biomass within a defined sourcing radius and minimum supply requirements. Farmers can therefore be willing to convert land but still be unable to deliver biomass if no processing facility with sufficient intake capacity is accessible. The analysis compares two processing routes: a biorefinery route, in which grass is processed in a green biorefinery, and a biogas route, in which it is used for biogas production. The model application is based on the Danish field and farm registers at field resolution (Landbrugsstyrelsen, 2026) and covers 28 simulated years in seven periods of four years. The results of the base scenarios are in each case the median of 100 model replications; where a range is given, it spans the 5th to the 95th percentile of the replications. The model description follows the Overview, Design concepts and Details (ODD) protocol [(Grimm et al., 2020); supplementary material].

D4.3 translates the main messages for policy audiences into a policy brief and summarises the work carried out in Task 4.1, which is documented in a comprehensive working report (Möhring et al., 2026).

Although the results presented here and the messages derived from them are based on a specific application of the ADAPtES model, they are transferable to the other case study sites of trans4num. This transferability lies, on the one hand, in the core model design for biomass value chains and, on the other, in the diagnostic question: which constraint is decisive, and which policy instrument can therefore influence the outcome? This policy brief is structured around this question.

2 Policy Brief

2.1 Key messages

Processing capacity at individual plants limits the value chain where many farmers are willing to convert; where few are willing, profitability does.

In every configuration more farmers are willing to convert than can deliver. At a trading radius of 20 kilometres and an area payment of 200 EUR per hectare, farm agents are willing to convert 6,729 fields, but only 3,801 deliver. Doubling the capacity of each plant raises the number of fields that farm agents are willing to convert by 15 %, but the number of delivering fields by 53 %. Without a payment, far fewer farmers are willing, and far fewer fields remain without access to a processor. Because the trading radius sets both the reach and the number of plants, many plants with intermediate catchments convert more land than few plants with wide catchments (35,719 against 28,050 hectares), but only at a payment of 200 EUR per

hectare. On the biogas route, the energy crop cap keeps the converted area below 10,000 hectares in all 100 runs.

At the assumed prices, the area payment carries a substantial part of the supply.

Without a payment, the grass rotation returns 55 to 74 EUR per hectare and year more than the arable rotation, only 7 to 10 % of the gross margin of the reference rotation. At 200 EUR per hectare, 31 to 36 % of the delivering fields depend on the payment. Its average public cost of 15 to 16 EUR per kilogram of nitrogen hardly differs between configurations. All biorefinery results assume a protein price of 1.92 EUR per kilogram of protein (dry matter basis), that farmers receive the full value of the products and that processing is not charged; they therefore represent an upper bound.

The value chain contributes to the regional nitrogen target but is not a standalone solution.

In the best configuration it reduces the nitrogen load by 246.3 t per year (5th to 95th percentile: 27 to 360 t). This covers up to 49 % of the reduction still required after the measures in the river basin management plan for 2027, 25 % if further efforts without defined instruments are excluded, and about 15 % of the total requirement of 1,615 t N per year (Miljøministeriet, 2023). In addition, about 3,812 t of nitrogen per year are incorporated into protein concentrate. This is a different flow, which describes nutrient recovery within the catchment rather than a reduction of the load to water.

The chain builds up within twelve simulation years; whether suppliers stay is mainly a matter of profitability. At 200 EUR per hectare, 45 to 73 % of the final converted area is reached after eight simulation years and the full level after twelve, when the first eight-year supply contracts expire. In individual runs the area then rises and falls with contract renewals: at the end of the simulation, it stands at 73 to 76 % of the run's own maximum at 10 and 20 kilometres, and at 42 to 52 % without a payment. The model results thus also provide insights into the dynamics of the value chain by simulating its evolution over time. An indicator taken only at the end of the simulation would miss both the speed of the build-up and the losses at contract renewal.

2.2 Context: why nitrogen instruments underperform

European agriculture is required to reduce nitrogen losses to coastal waters while maintaining production and farm income (EC, 2025; European Parliament and Council, 2000; Ministry of Green Transition, 2025). Green biorefining, in which grass-clover is fractionated into a protein concentrate, a fibre fraction and a residual juice, addresses both objectives at once: the perennial ley leaks substantially less nitrogen than the arable rotation it replaces, and the protein fraction substitutes for imported feed protein (Energibyen Skive and Skivekommune, 2025; Graversgaard, 2025; Strunge Folkmann, 2025).

The practice is technically established and is supported in several Member States (Gaffey, 2026). Adoption nonetheless remains far below the level that public support schemes anticipate. The usual explanation is that farmers are reluctant, and the common response is to increase payment per hectare. In the Skive area, local stakeholders are discussing an area payment of about 200 EUR per hectare for grass-clover delivered to green biorefining (Klimafonden Skive, 2025).

2.3 Results

The evidence presented here suggests that the situation in the sourcing area of a processing plant in the grass-clover value chain is more complex, and that an area payment is only partly effective where processing capacity is limited: it raises the number of farmers willing to convert, but not all of them can deliver. Figure 1 shows the median number of fields whose farm agents are willing to adopt and of fields whose farm agents actually deliver at the end of the simulation, by trading radius and payment level. Willingness exceeds delivery in every configuration. The distance between the two lines indicates the fields whose farm agents would convert but have no access to a processor, either because no plant is within reach or because the nearest plant has no free capacity. Without a payment, both numbers are small and close to each other. At 200 EUR per hectare, willingness rises four- to fivefold at every radius, and at 20 kilometres delivery falls clearly behind. The shaded areas show how widely the results vary between model runs.

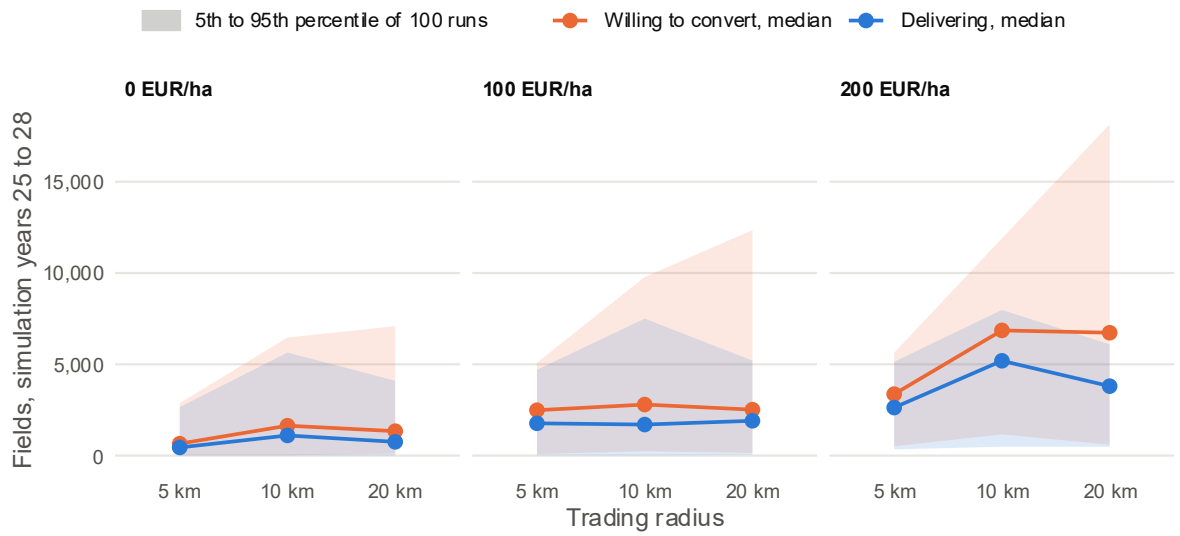


Figure 1: Fields of "willing-to-adopt" farm agents and fields of "delivering" farm agents at the end of the simulation (simulation years 25 to 28), by trading radius and payment level.

Note: Lines: median of 100 runs; shaded areas: 5th to 95th percentile. Source: (Möhring et al., 2026)

Table 1 adds the outcome of each radius at 200 EUR per hectare. It shows the converted area and the nitrogen reduction at the end of the simulation. The intermediate radius of 10 kilometres gives the largest converted area and the largest nitrogen reduction. At 20 kilometres, farm agents are willing to convert roughly the same number of fields as at 10 kilometres. However, about a quarter fewer fields deliver than at 10 kilometres (3,801 against 5,191), and the converted area is around a fifth smaller. At 5 kilometres fewer farmers are willing, but most of them can deliver. The ranges in brackets are wide and overlap between the radii; the ordering is therefore a tendency across runs, not a result that holds in every run.

Table 1: Willingness, delivery and outcome by trading radius, at a payment of 200 EUR per hectare and year.

Trading radius	Fields of willing-to-adopt farm agents	Fields of delivering farm agents	Fields without access to a processor	Area under grass [ha]	Nitrogen reduction [t N yr^{-1}]
5 km	3,366	2,628	401	17,239 (2,361 to 34,082)	115.8 (16.7 to 212.9)
10 km	6,856	5,191	1,452	35,719 (3,500 to 54,786)	246.3 (27.3 to 360.4)
20 km	6,729	3,801	3,220	28,050 (4,031 to 45,613)	202.0 (36.6 to 325.1)

Note: Medians of 100 replications at the end of the simulation (simulation years 25 to 28); in brackets the 5th to 95th percentile. Medians of different quantities do not add up, so the three field columns are not additive. Source: (Möhring et al., 2026).

The following findings each have a direct implication for the choice of policy instrument.

At 200 EUR per hectare, processing capacity at individual plants rather than farmer willingness determines the outcome. When the intake capacity of each facility at the 20-kilometre radius is doubled and nothing else changes, the number of fields of willing-to-adopt farm agents rises by 15 % (from 6,729 to 7,758), while the number of fields of delivering farm agents rises by 53 %. The converted area increases by 45 % and the nitrogen reduction by 93.5 t N per year, from 202.0 to 295.5 t (Figure 2). Halving the capacity reduces the converted area by 31 %. Willingness is largely present, but what limits the outcome is the ability to deliver. The constraint is local rather than sector-wide: at the end of the simulation the plants at 20 kilometres use on average 63 % of their total intake capacity (Table 2). In the model, each field of a willing-to-adopt farm agent is offered only to its nearest plant, so it remains without access when that plant is full. Some plants therefore reach their limit while unused capacity remains elsewhere in the region, and many willing farmers are left without an outlet. This assignment rule is a model simplification and is likely to overstate the local constraint.

Coverage matters more than scale. The trading radius determines how many farm agents a facility can reach and, at the same time, how many facilities are founded, because a wide sourcing area allows a single facility to meet its minimum supply from a large area. The two effects act in opposite directions (Table 2). At 5 kilometres, 17 plants are founded, but each reaches few fields, and the plants use only a quarter of their capacity. At 20 kilometres each plant reaches many fields, but only 11 plants are founded. At 10 kilometres, 16 plants with medium-sized sourcing areas cover 35,719 hectares, whereas the 11 plants with large sourcing areas at 20 kilometres cover 28,050 hectares, with an identical capacity per facility. Many medium facilities therefore tend to outperform few large ones. The advantage appears only at 200 EUR per hectare, where many farmers are willing and capacity binds at individual

plants; without a payment and at 100 EUR per hectare, the two radii do not differ beyond the variation between runs.

Table 2: Processing sector by trading radius, at a payment of 200 EUR per hectare and year.

Trading radius	Biorefineries [number]	Total intake capacity [1,000 t FM yr^{-1}]	Capacity used [%]	Area under grass [ha]
5 km	17 (13 to 17)	3,672	25 (4 to 55)	17,239
10 km	16 (14 to 18)	3,456	53 (5 to 82)	35,719
20 km	11 (8 to 13)	2,376	63 (9 to 91)	28,050
20 km, capacity halved	11 (7 to 13)	1,529	66 (9 to 98)	19,331
20 km, capacity doubled	11 (8 to 13)	4,752	41 (4 to 84)	40,628

Note: Medians of 100 replications at the end of the simulation (simulation years 25 to 28); in brackets the 5th to 95th percentile. Intake capacity per plant 216,000 t fresh matter per year (139,000 and 432,000 t in the capacity variants). Capacity used: grass delivered to biorefineries divided by the total intake capacity of the active plants. Source: (Möhring et al., 2026).

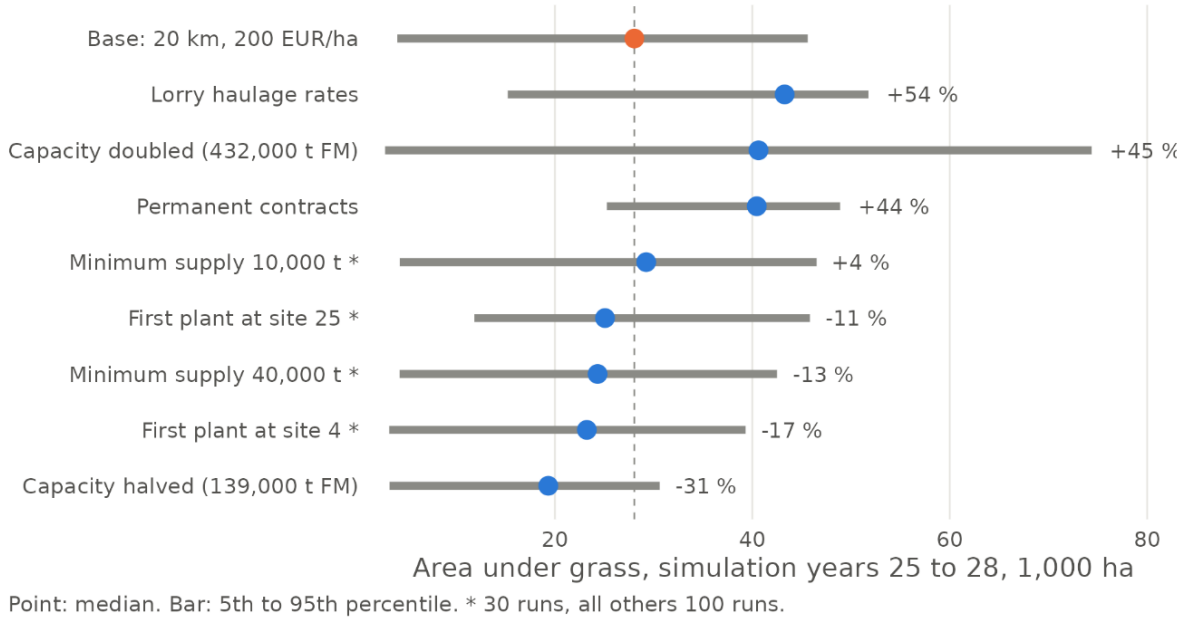


Figure 2: Sensitivity of the converted area at the end of the simulation (simulation years 25 to 28) to single parameters, at 20 kilometres and 200 EUR per hectare.

*Note: Points: median; bars: 5th to 95th percentile; * 30 runs, all others 100 runs. Source: (Möhring et al., 2026).*

The grass rotation pays for itself only narrowly, and the area payment carries part of the supply. With a payment of 200 EUR per hectare, 31 to 36 % of the delivering fields depend on it, and on average over the delivering fields the margin without the payment is negative (−37 to −74 EUR per hectare and year). The payment therefore does not only reach farms that would have converted anyway; it also keeps fields in the chain that would otherwise not deliver. Raising the payment from 100 to 200 EUR per hectare costs 25 to 34 EUR per additional kilogram of nitrogen removed. At 200 EUR per hectare, the average public cost is 15 to 16 EUR per kilogram of nitrogen in all five configurations, because a payment per hectare pays the same for a field that removes much nitrogen as for one that removes little.

The results depend on the price of the protein fraction. The farm margin rests on a protein price of 1.92 EUR per kilogram of protein (dry matter basis) (Strunge Folkmann, 2024) and on the assumption that the full value of the products accrues to the supplier of the biomass, with no charge for processing. This price assumes that one quarter of the protein is sold as food-grade protein at the value of milk protein; valuations of feed-grade protein alone are about 1.04 EUR per kilogram (Termansen et al., 2016). The results therefore describe the most favourable division of the chain margin. The margin of 55 to 74 EUR per hectare without a payment is small compared with the processing costs of a decentralised plant, about 32 EUR per tonne of dry matter (Hermansen et al., 2017), or roughly 300 EUR per hectare at the modelled yield. How far the converted area falls when part of these costs is passed on to the farmer, and which payment would then be needed to keep supply in the chain, is the subject of further work.

The biogas route is limited by regulation as well as by economics. Whole-crop grass delivered to a biogas plant is classified as an energy crop under Danish law, and energy crops are capped at 4 % of the weight input of a plant [BEK nr. 494 af 16/05/2025, (Klima-, Energi- og Forsyningsministeriet, 2025)]. Fibre and brown juice returned from a biorefinery are processing residues, which the same legislation favours over energy crops, and the cap does not apply to them. The biogas route therefore operates under a ceiling that the biorefinery route does not face. Where grass is delivered to a biogas plant, the protein fraction is not valued, and without a payment the grass rotation earns about the same as the arable rotation (7 to 14 EUR per hectare and year more). The payment therefore changes farmers' decisions: under the cap, a payment of 200 EUR per hectare raises the number of fields that farm agents are willing to convert about threefold (from 179 to 568) and the number of delivering fields about fourfold (from 55 to 228). Delivery nevertheless remains small: in all 100 runs the converted area stays below 10,000 hectares, with a median of 1,833 hectares. Without the cap the area is about four times larger (7,664 hectares), but it remains well below that of the biorefinery route at the same payment (17,239 to 35,719 hectares).

The chain builds up quickly, but whether it holds depends on contract renewal. Figure 3 shows the converted area over the simulated years at 10 and 20 kilometres, without a payment and at 200 EUR per hectare. The median, shown as a line, reaches its final level after about twelve simulation years, when the first eight-year supply contracts expire. The individual runs, shown in grey, rise and fall with contract renewals at different times, because farm agents decide again at each renewal whether to continue. With a payment, a larger share of the area is therefore retained. Contract design and logistics also matter: permanent contracts raise the converted area at the end of the simulation by 44 %, and lower haulage

costs, as with contracted lorry transport instead of tractors, by 54 %, without public expenditure (Figure 2).

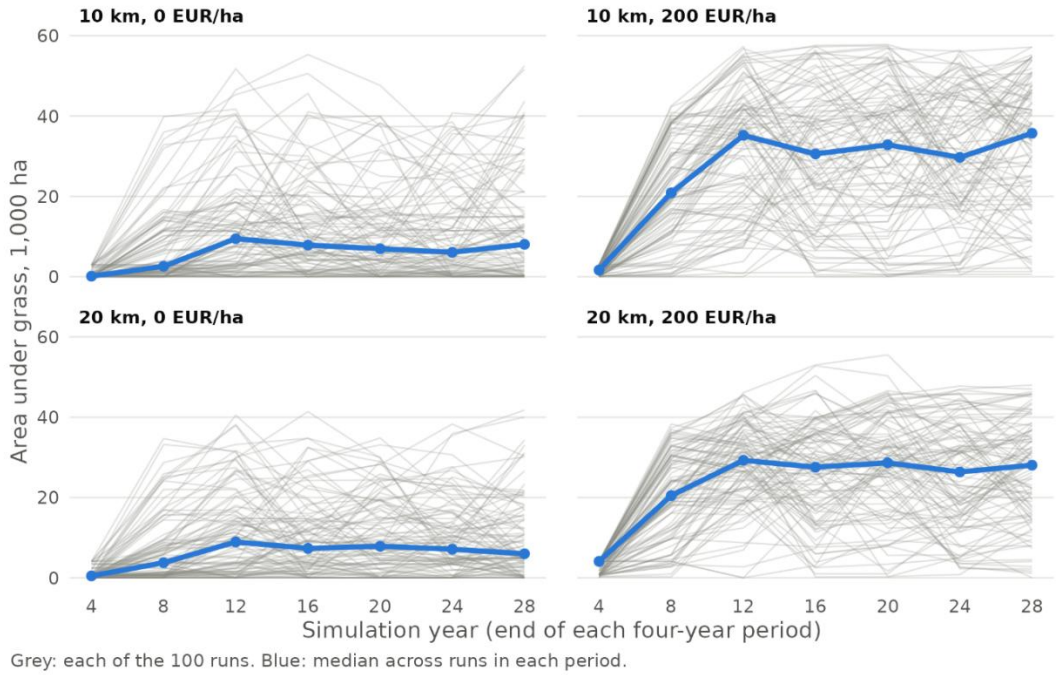


Figure 3: Converted area over the simulated years at 10 and 20 kilometres, without a payment and at 200 EUR per hectare.

Note: Grey: each of the 100 runs; blue: median across runs in each four-year period. Source: (Möhring et al., 2026).

Nitrogen: contribution to the regional target and nutrient flows. Figure 4 compares the nitrogen reduction of all configurations with the reduction required in the two sub-catchments under the river basin plan [water catchments #157 and #158]. The biorefinery configurations at 200 EUR per hectare come closest, but in the median none reaches the remaining requirement. If each plant at 20 kilometres were twice as large, the reduction would rise from 202.0 to 295.5 t per year. That would still cover only part of the remaining requirement: 58 %, or 31 % if further efforts without defined instruments are excluded. It would also require plants twice the size assumed here, whose investment and operating costs are not part of this assessment, and more than half of the total capacity would remain unused (Table 2). Besides reducing the nitrogen load, the chain moves about 3,812 t of nitrogen per year into protein concentrate, the nitrogen equivalent of 4.3 % of Danish soybean meal imports, and about 5,700 t per year leave the plants in digestate. These flows describe nutrient recovery rather than progress towards the water-quality objective and cannot be added to the load reduction. The model reports the load from converted fields rather than a closed nutrient balance, and it does not track where this nitrogen is applied.

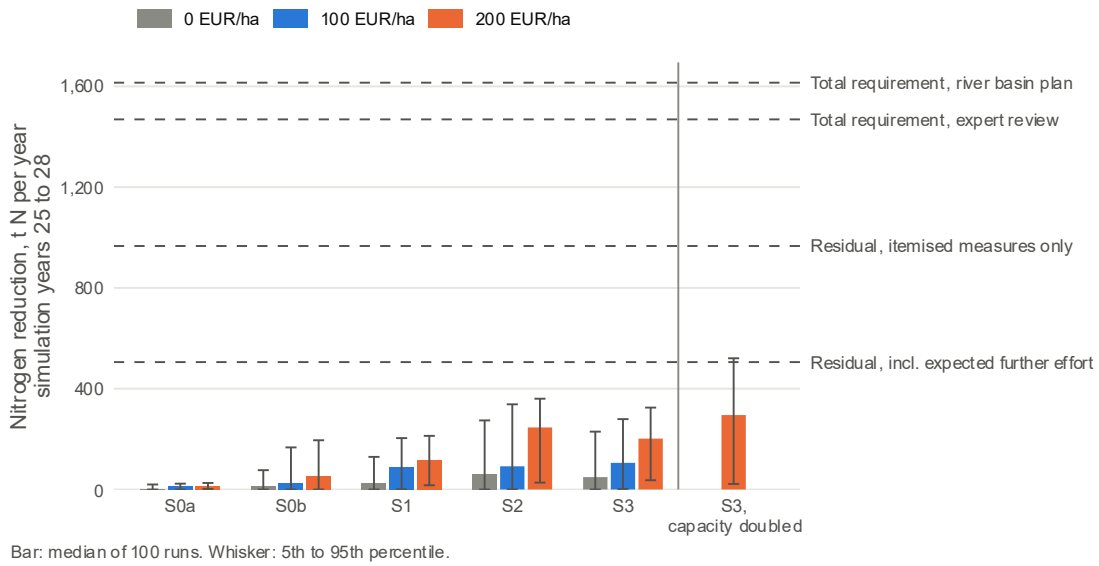


Figure 4: Nitrogen reduction at the end of the simulation (simulation years 25 to 28) against the requirements of the river basin plan for water catchments #157 and #158.

Note: Bars: median of 100 runs; whiskers: 5th to 95th percentile. S0a and S0b: biogas only, with (a) and without (b) the energy crop cap; S1 to S3: biorefinery and biogas with a trading radius of 5, 10 and 20 kilometres. Source: (Finansministeriet et al., 2024; Miljøministeriet, 2023; Möhring et al., 2026).

2.4 Policy recommendations

Recommendation 1. Diagnose the binding constraint before selecting the policy instrument

For EU institutions and Member State authorities.

The same model applied at the project's Chinese site finds that a subsidy is what moves adoption, because the obstacle there is a persistent profitability gap (Liu et al., 2026). In the Danish Limfjord both constraints are present: profitability determines how many farmers are willing to convert and how many stay at contract renewal, and processing capacity determines how many of the willing-to-adopt farm agents can deliver. While the results of this case study approach cannot be generalised across the EU, the diagnostic method used to produce them can. Before a policy instrument is selected, appraisal of nutrient measures should establish whether the limiting factor is farm profitability, processing capacity, regulatory constraints or spatial coverage. This is because a policy instrument matched to the wrong constraint can be fully taken up and have little effect.

Recommendation 2. Combine support for processing capacity with area payments

For Member State authorities designing support for green biorefining; for EU institutions in the design of bioeconomy and rural investment instruments.

Where processing capacity binds at individual plants, part of the willingness created by an area payment cannot be delivered. Public support for increasing intake capacity addresses this constraint most directly where it is targeted at plants with more willing suppliers than capacity, rather than spread evenly across the sector. Because a substantial share of the delivering fields depends on the area payment, capacity support should complement the payment rather than replace it. The area payment itself is better understood as support for retention and as insurance against price risk than as a means of controlling volume.

Recommendation 3. Coordinate the location of facilities across administrative districts

For Member State and regional authorities.

Facilities should be sited under a plan formed at district level rather than approved case by case, so that the resulting network tends towards many medium sourcing areas rather than few large ones, and so that capacity is available where farmers are willing to supply it. Case-by-case approval is likely to produce the second pattern, with few processors and large sourcing areas, because each applicant has an incentive to claim the widest sourcing area available.

Recommendation 4. Direct support for grass-clover primarily to the biorefinery route

For Danish authorities designing support schemes.

Under Danish law, the energy crop cap applies to whole-crop grass delivered to biogas plants, but not to fibre and brown juice from a biorefinery. In the model, the cap keeps the biogas route small in every run, and even without the cap the biogas route remains well below the

biorefinery route. Where grass-clover is promoted to reduce nitrogen losses, support should therefore be directed primarily to the biorefinery route. Transitional arrangements, such as allowing grass to be delivered to biogas plants until a biorefinery is available, were not assessed here.

Recommendation 5. Design supply contracts for stable delivery.

For processors, and for authorities designing support schemes.

Supply fluctuates at contract renewal, when farmers decide again whether to continue. Processors should stagger contract start dates, so that no single expiry year removes a large share of supply at once and consider longer contract terms. Capacity should be planned for the area that remains supplied after renewal, not for the highest area reached. Lower haulage costs, for example through contracted lorry transport, also stabilise supply without public expenditure.

Recommendation 6. Assess water-quality effects and wider nutrient effects separately.

For river basin authorities and EU institutions appraising nutrient measures.

The value chain affects nitrogen in two different ways. The reduction in nitrogen loss from converted land directly serves the water-quality objective, while the nitrogen incorporated into protein feed and returned as digestate illustrates the recovery and redistribution of nutrients within the value chain. These quantities should not be treated as equivalent environmental benefits. A complete assessment should consider both, avoid double counting, and account for where the recovered nitrogen is eventually applied. A regional nutrient balance, such as the decision-support tool developed in trans4num (Frick et al., 2026), is the appropriate tool for this purpose.

3 Conclusion

Four conclusions carry beyond the Limfjord water catchment.

i. Willingness, processing capacity and realised delivery should be distinguished and followed over time. In the model, high willingness to adopt does not translate into high delivery where access to processing is constrained, and the course over time shows whether supply holds at contract renewal. For monitoring, processing capacity and actual delivery are easier to observe than farmer willingness. Their ratio for the sector as a whole is, however, not sufficient: in the model, plants at 10 and 20 kilometres use on average 53 to 63 % of their capacity while many willing farmers have no outlet, because capacity binds at individual plants. Monitoring should therefore record capacity use per plant, as well as the number of suppliers that each plant turns away. Willingness remains necessary as an analytical concept, because it identifies potential supply, which the model estimates explicitly and which cannot be observed from throughput alone.
ii. The choice of policy instrument should follow a diagnosis of the constraint. Where processing capacity binds at individual plants, an area payment raises willingness, but

part of it cannot be delivered; where profitability binds, the payment is what keeps supply in the chain. In the Limfjord both constraints apply, depending on the level of the payment.

iii. A value chain analysis limited to the environmental indicator provides an incomplete assessment of the intervention. The reduction in nitrogen load is real and is what a water authority can count. It does not, however, replace a nutrient balance of the whole value chain.

iv. An agent-based approach that answers "what if" questions while representing the heterogeneity of farmers' decisions and their interaction with processors can be transferred to other sites and nature-based solutions and covers both the crop rotation and the value chain as a whole. It can therefore support the design of policy instruments for circular, resource-efficient value chains.

Outlook: The complexity of the green biorefinery value chain could not be fully captured by the model calculations presented here. The results describe the most favourable distribution of the chain margin, as farmers receive the full value of the products and processing is not charged. Furthermore, each field of a willing-to-adopt farm agent is offered only to its nearest processing plant, which is likely to overstate local capacity constraints. How the results change if processing costs are passed on to farmers is the subject of further investigation.

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5 Appendix 1: Evidence Map

Appendix 1: Evidence map for the claims of the policy brief. Values are medians of 100 replications at the end of the simulation (simulation years 25 to 28), unless stated otherwise; ranges are 5th to 95th percentiles.

#	Claim	Evidence in this deliverable	Strength	What does it not show?	Where
1	Where many farmers are willing to convert, processing capacity at individual plants limits delivery	At 20 km and 200 EUR/ha, doubling the capacity per plant raises the number of fields that farm agents are willing to convert by 15 %, the number of delivering fields by 53 %, the converted area by 45 % and the nitrogen reduction by 93.5 t N/yr; halving it reduces the area by 31 %. The plants use on average 63 % of their total capacity	**Strong** within the model: one parameter varied, 100 runs; the spread between runs is wide	Whether plants of that size can be financed and operated. Each field is offered only to its nearest plant, a simplification that is likely to overstate the local constraint	Key message 1; Results, first finding; Table 2; Figure 2
2	Where few farmers are willing, profitability limits the value chain	Without a payment, farm agents are willing to convert far fewer fields (652 to 1,637), few fields remain without access to a processor (144 to 326), and the plants use 9 to 34 % of their capacity at 0 and 100 EUR/ha	**Moderate**: comparison of medians across payment levels, not a separate experiment	At which margin the constraint switches from profitability to capacity	Key message 1; Figure 1; Table 1
3	Many plants with medium sourcing areas tend to outperform few plants with large ones	At 200 EUR/ha: 16 plants at 10 km cover 35,719 ha, 11 plants at 20 km cover 28,050 ha, with the same capacity per plant. At 0 and 100 EUR/ha the two radii do not differ beyond the variation between runs	**Moderate**: holds only at 200 EUR/ha; three radii tested	The optimal radius (no continuum tested); how real siting decisions are made	Key message 1; Results, second finding; Table 2; Recommendation 3
4	At the assumed prices, the area payment carries a substantial part of the supply	Without a payment the grass rotation returns 55 to 74 EUR/ha/yr more than the arable rotation (7 to 10 % of its gross margin). At 200 EUR/ha, 31 to 36 % of the delivering fields depend on the payment, and the margin without the payment is on	**Strong** within the model, but conditional on the price assumptions in row 6	Farm margins under a realistic division of the chain margin	Key message 2; Results, third finding; Recommendation 2

#	Claim	Evidence in this deliverable	Strength	What does it not show?	Where
		average negative over the delivering fields (−37 to −74 EUR/ha/yr)			
5	The average public cost per kg of nitrogen does not help to choose between configurations	At 200 EUR/ha, 15.0 to 16.4 EUR/kg N in all five configurations; raising the payment from 100 to 200 EUR/ha costs 25 to 34 EUR per additional kg N in the biorefinery configurations	**Strong**, arithmetic in origin: a flat payment per hectare pays the same for every field	The cost-effectiveness of instruments that are not paid per hectare	Key message 2; Results, third finding
6	The results are an upper bound	Protein price 1.92 EUR/kg protein (DM basis), assuming one quarter food-grade protein; feed-grade valuations about 1.04 EUR/kg. The farmer receives the full product value and processing is not charged. The margin without a payment (55 to 74 EUR/ha) is small against processing costs of a decentralised plant (about 32 EUR/t DM, roughly 300 EUR/ha)	**Assumption**, not tested in this deliverable	How far supply falls when processing costs are passed on to the farmer, and which payment would then keep it in the chain (further work)	Key message 2; Results, protein price paragraph
7	The energy crop cap limits the biogas route	Under the cap (4 % of the weight input of a plant) the converted area stays below 10,000 ha in 100 of 100 runs (median 1,833 ha). Without the cap it is about four times larger (7,664 ha), but remains below the biorefinery route at the same payment (17,239 to 35,719 ha)	**Strong** within the model	Exemptions the model does not represent, which may make the model overstate the effect of the cap; transitional arrangements	Key message 1; Results, biogas paragraph; Figure 4; Recommendation 4
8	The chain builds up within twelve simulation years; whether it holds depends	At 200 EUR/ha, 45 to 73 % of the final area after eight simulation years, the full level after twelve. At the end of the simulation the area stands at 73 to 76 % of the run's own maximum at 10 and 20 km, and at 42 to 52 %	**Moderate:** contract and haulage variants each 100 runs	Real contract structures; staggered contract start dates were not simulated	Key message 4; Results, contract renewal paragraph; Figures 2 and 3;

#	Claim	Evidence in this deliverable	Strength	What does it not show?	Where
	on contract renewal	without a payment. Permanent contracts raise the final area by 44 %, lorry haulage rates by 54 %			Recommendation 5
9	The value chain contributes to the regional nitrogen target but cannot meet it alone	246.3 t N/yr (27 to 360 t) in the best configuration: 49 % of the residual after the measures budgeted for 2027, 25 % if further efforts without defined instruments are excluded, 15 % of the total requirement of 1,615 t N/yr. Doubled capacity per plant: 295.5 t N/yr	**Strong** within the model; an upper bound (row 6)	Which residual applies; the net effect on the catchment (field load, not a nutrient balance)	Key message 3; Results, nitrogen paragraph; Figure 4
10	Nitrogen in products and the reduction of the nitrogen load are different flows	About 3,812 t N/yr enter the protein concentrate (4.3 % of the nitrogen in Danish soybean meal imports) and about 5,700 t N/yr leave the plants in digestate, against a load reduction of 246.3 t N/yr	**Strong** that the two are different flows. **Moderate** for the quantities: they follow from fixed fractionation and protein coefficients taken from the literature, and they scale with the converted area, which is an upper bound (row 6)	Whether the protein displaces imported feed; where feed and digestate nitrogen is applied and how much of it is lost	Key message 3; Results, nitrogen paragraph; Recommendation 6

6 Appendix 2: ODD Protocol

This is being delivered as supplementary material.

Appendix 2 of Deliverable D4.3:

ODD protocol of ADAPtES

Agent-based Diffusion modelling system of Agricultural Practices towards Ecosystem Services

30.09.2026

Supplementary material
Version 2

Funded by
the European Union

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The description follows the Overview, Design concepts and Details (ODD) protocol of (Grimm et al., 2020). It describes the model as implemented for the Danish case study site of trans4num. The ODD has been submitted as supplementary material in Appendix 2 of Deliverable D4.3.

1 Overview

1.1 Purpose and patterns

ADAPtES assesses the adoption and diffusion potential of nature-based solutions (NBS) for circular nutrient management in agricultural regions, and the consequences of adoption for the value chain that processes the biomass. This Agent-Based Model (ABM) is designed for policymakers and stakeholders who need to assess how far a land use change can spread under a given policy instrument and a given processing infrastructure, and what the change costs per unit of environmental effect.

For the Danish site the practice under study is the substitution of a grass and clover ley for part of a cereal, maize or potato rotation, with the grass delivered either to a green biorefinery or to a biogas plant. The model was designed to reproduce three patterns:

1. Adoption follows an S-shaped curve in time, as the diffusion literature suggests (Alexander et al., 2013; Rogers et al., 2019)
2. Adoption is spatially clustered around processing facilities, because transport cost rises with distance and fresh grass cannot be stored.
3. The area actually converted stays below the area farmers are willing to convert whenever processing capacity or facility reach is limiting. The gap between the two is a model output in its own right.

The model is not a forecast. It is a comparative device: differences between scenarios carry the information, absolute levels do not.

1.2 Entities, state variables and scales

The model contains four types of entity. First**, farmers** are the decision-making agents. A farmer holds one or more fields, and all fields of a farmer share the farm level attributes. Second, **processors** are biorefineries and biogas plants. They are not decision makers: they accept or reject deliveries according to reach and capacity, and biorefinery sites become active endogenously when the supply within their reach is sufficient. Third, **parish polygons** define the spatial environment and the neighbourhood through which the social signal travels. Fourth, **fields** are the objects on which decisions are resolved, because the model is spatially explicit and transport distance is a field attribute.

The distinction matters for reading the results. The agents are farmers and processors. The decision unit is the field, because two fields of the same farm can differ in distance to the nearest facility and therefore in the profitability of the grass option. Therefore, in our model, a farmer is assigned a value for their willingness to adopt, the adoption of each of their fields depends on its profitability, which is affected by transport costs.

Table 1: State variables of the model entities.

Entity	State variable	Symbol	Source
Farmer	Farm identifier		Field register, farm level aggregation
	Innovation segment		Probit model, Section 3.3.4
	Adoption threshold	AT	Probit model, Section 3.3.4
Field	Area	a	Field register
	Parish		Parish boundaries
	Reference rotation (1, 2, 3)		Observed 7yr crop sequence
	Straight-line distance to nearest candidate biorefinery site	d_R	Field and site coordinates
	Road distance to nearest biogas plant	d_G	Pre-processed road network
	Baseline nitrogen leaching	L_{BAU}	Parish × rotation distribution
	Nitrogen retention	RET	Parish × rotation distribution
	Adoption state	a?	Endogenous
	Willingness	willing?	Endogenous
	Contract state, expiry		Endogenous
	Neighbourhood adoption signal	AR	Endogenous
Processor	Type (biorefinery, biogas)		Facility register
	Location		Facility register

Entity	State variable	Symbol	Source
	Trading radius	r	Scenario parameter
	Annual capacity	K	Scenario parameter
	Remaining capacity in the period		Endogenous
	Active or inactive (biorefineries)		Endogenous
Parish	Identifier, centroid		Parish boundaries
	Adjacent parishes		Neighbourhood file

Scales: One time step represents four years, which is the length of one grass period and of the compressed reference rotation. The model runs seven steps, t = 0 to 6, each representing four years, so the simulated horizon is 28 years. At t = 0 the gross margins are set to their deflated 2008 to 2023 means; farmers already decide in this first period. The spatial extent is the Danish Limfjord catchment sub-areas 157 and 158 in Northern Jutland, 2,621 km², divided into 416 parishes. The region holds 57,422 fields on 255,238 ha belonging to 2,426 farms; 23,111 fields on 162,903 ha held by 1,757 farms satisfy the suitability conditions of Section 3.3.1.

1.3 Process overview and scheduling

Each time step executes the following procedures in a fixed sequence (Figure 1):

1. **Update accessibility.** For every field, determine whether a facility lies within its trading radius.
2. **Profit.** Draw the stochastic yield, price and cost parameters of the period and compute the gross margins of the reference rotation and of the grass rotation.
3. **Cultivate.** For every eligible field, compute the profit difference and set willingness value.
4. **Update the social signal. Recompute** the neighbourhood adoption signal AR from the willingness and profit sign of neighbouring fields.
5. **Facility activation.** Assess whether an inactive biorefinery site has now accumulated sufficient claimable supply to become operational, and if so, open the single most suitable site.
6. **Delivery allocation.** Assign fields of willing-to-adopt farmer agents to facilities based on reach and remaining capacity. Each field of a willing-to-adopt farm agent is offered only to its nearest active biorefinery. If that plant lies within the trading radius and has free capacity, the field is admitted, closest fields first. Fields without an outlet remain willing but do not deliver, even if another plant within reach has spare capacity.

7. **Contract expiry.** Re-evaluate contracts that have reached their term and either renew or release them.
8. **Accounting.** Calculate the land allocated, the processing mass balance, nitrogen balance and output indicators; then write the period record.
9. **Advance. Advance the model by** one tick.

The aforementioned sequence is not neutral. Accessibility precedes willingness, so a field outside every trading radius never becomes willing, regardless of its profitability. Willingness precedes delivery, so the model distinguishes farmers who want to convert from farmers who can. That distinction is the source of the number of fields without access to a processor reported in the policy brief. Figure 2 shows the resulting status of every field for four configurations.

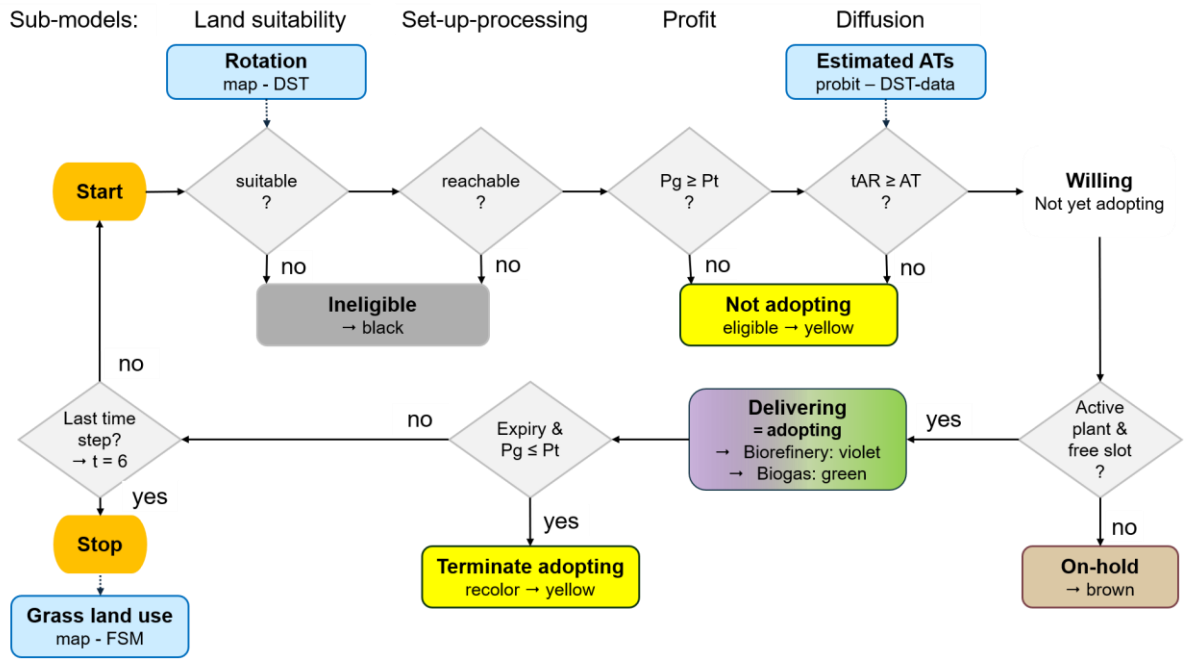


Figure 1: Process overview.

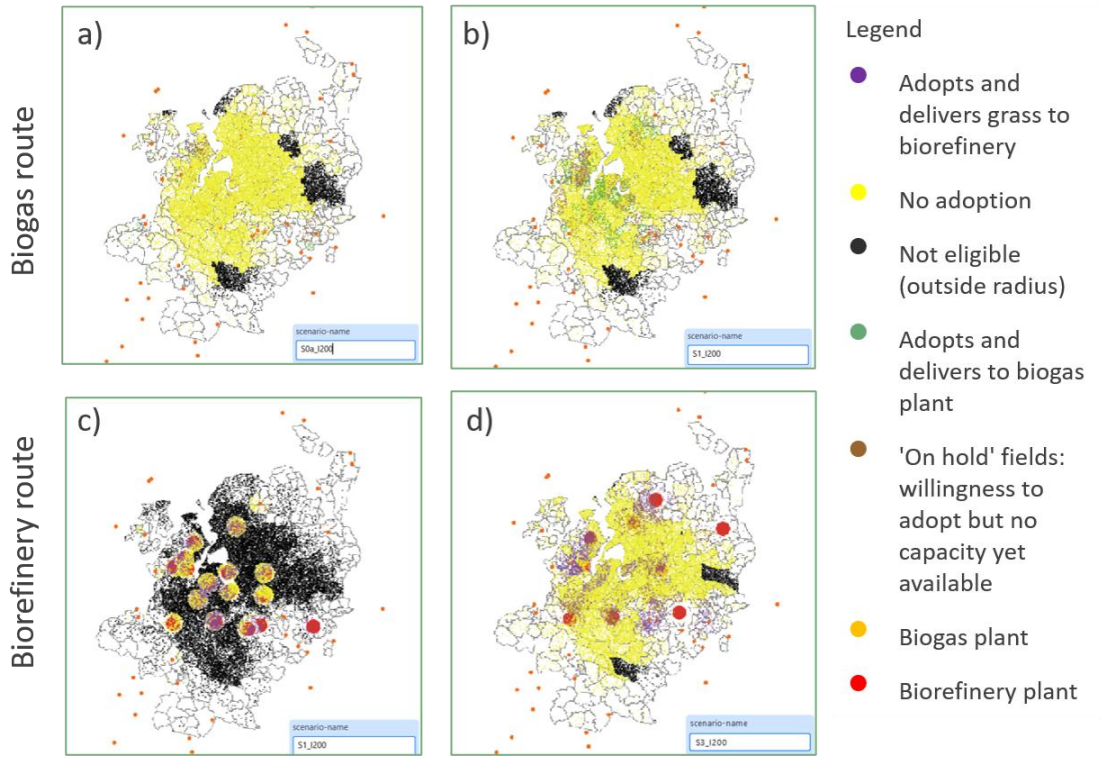


Figure 2: Status of every field at the end of one simulation run (simulation years 25 to 28), four configurations at a payment of 200 EUR per hectare.

The maps show a single run and illustrate the spatial pattern, not the quantities; all quantities in the policy brief are medians of 100 runs. Top row: biogas route, with grass delivered whole to existing biogas plants. Bottom row: biorefinery route; red points mark the biorefineries established in the run. a) S0a, biogas route with the energy crop cap; b) S0b, biogas route without the cap; c) S1, biorefinery route with a trading radius of 5 kilometres; d) S3, biorefinery route with a trading radius of 20 kilometres. Black fields lie outside the trading radius of any processor; brown fields belong to farm agents that are willing to convert but have no access to a processor, either because no plant is within reach or because the nearest plant is full. Comparing c) and d) shows the trade-off between reach and capacity described in the policy brief: a small radius leaves most of the area out of reach, a wide radius reaches most fields, but many of them do not deliver.

2 Design concepts

2.1 Basic principles

Three principles found the model. First, farmers maximise expected profit over the planning horizon of one grass period, discounted at a real rate. Second, farmers are influenced by what comparable farmers in their own and adjacent parishes do, following diffusion of innovation theory (Rogers et al., 2019). Third, adoption requires a counterpart: the practice is only available where a processor can be reached, so the spatial structure of the processing industry is part of the adoption problem and not a boundary condition.

2.2 Emergence

The adoption path over time, the spatial pattern of adoption, the number and location of active biorefineries, the volume and composition of processed biomass, and the reduction in nitrogen leaching emerge throughout the simulation procedure. None of them is imposed. The gap between fields-willing-to-adopt and delivering area emerges from the interaction between the diffusion process and the capacity of the processing sector and is the property that separates the scenarios most sharply.

2.3 Adaptation

A field is converted to the grass rotation when both of the following hold:

- the discounted profit of the grass rotation exceeds that of the reference rotation, and
- the neighbourhood adoption signal reaches the farmer's adoption threshold.

Formally, with ΔP the profit difference of Section 3.3.3 and AR the signal of Section 3.3.4,

$$willing = 1, \qquad if\ \Delta P\ > 0\ and\ AR\ \geq AT$$
$$willing = 0, \qquad otherwise$$

These conditions operate jointly, not as alternatives. Profitability alone does not produce adoption, nor does social imitation alone. A farmer already under contract is considered willing by definition until the contract expires.

2.4 Objectives

Farmers pursue the discounted profit of the field over one grass period. The model contains no risk aversion parameter and no utility function beyond profit. Processors have no objective function; their behaviour is a set of accept and reject rules.

2.5 Learning

The model does not implement learning. Farmers do not update their expectations about prices or yields from experience.

2.6 Prediction

Farmers make no explicit forecast of system dynamics. The discounting of the profit stream over the grass period is an implicit prediction that current conditions persist for four years.

2.7 Sensing

A farmer uses information on the yields, prices and costs of the current period; the area, soil and nitrogen attributes of the fields held; the road distance to the nearest biorefinery site and to the nearest biogas plant; whether these facilities lie within the trading radius; and the willingness and profit outcome of fields in the farmer's own and adjacent parishes. Farmers do not observe the remaining capacity of a facility. A capacity constraint is revealed only when a farmer fails to obtain a delivery slot. Consequently, the number of fields that farm agents are willing to convert can exceed the number of fields that can actually deliver.

2.8 Interaction

There are two interactions. The first is between farmers, the neighbourhood signal transmits the decisions of others; the transmission is indirect and unweighted, and it runs through the parish adjacency graph rather than through named social ties. The second is between farmers and processors; the interaction is a delivery contract, constrained by reach and by remaining capacity, and priced through the transport cost the farmer bears.

2.9 Stochasticity

The model incorporated four sources of randomness:

1. The gross margins of the reference crops and the grass dry matter yield are drawn from normal distributions once per period at landscape level.

2. Baseline nitrogen leaching and nitrogen retention are drawn per field at initialisation from parish × rotation distributions.
3. Fields are allocated to innovation segments at random within each parish × rotation cell, in the proportions given by the probit model.
4. Active plants are processed in random order; at each plant, fields are admitted in order of distance, closest first.

Because the yield and price draws are made once per period for the whole landscape, two runs that differ only in their random seed can differ systematically in outcome. Single run comparisons between scenarios are therefore not valid. The base scenarios are ensembles of 100 replications; the sensitivity runs on minimum supply and on the location of the first plant use only 30 replications. Results are reported as medians with the 5th to 95th percentile.

2.10 Collectives

The model contains no formal collectives or cooperative entities. Supply groups formed around active biorefineries emerge from individual farmer decisions and interactions, and they are not represented as agents.

2.11 Observation

At each step-period the model records the “willing” area and the “delivering” area, the number of fields in each state, the number of active facilities, the mass balance of the processing chain fractioned into fresh and dry matter, the recoverable methane energy, the protein and digestate nitrogen, the nitrogen leaching of the landscape and the reduction against the no-adoption baseline, the discounted profit difference with and without the payment, the public expenditure on the payment, and the number of contract exits. The record is written as one row per four-year-period and replication.

3 Details

3.1 Implementation

The model is implemented in NetLogo 7.0.3 (Wilensky, 2024). Data preparation, spatial pre-processing and analysis use R 4.3.0 and QGIS 3.28. The model concept follows (Ullah et al., 2023; Ullah and Crooks, 2023), extended by the endogenous activation of processing facilities, the capacity and contract mechanisms, the mass balance of the processing chain, and the empirical estimation of adoption thresholds following (Grovermann et al., 2017).

Modularity. The model runs with or without the empirical adoption thresholds. With use-probit? = true (Mode A) thresholds come from the probit model of Section 3.3.4 and are farm specific. With use-probit? = false (Mode B) thresholds are drawn from a parametric distribution for all fields, following (Alexander et al., 2013; Ullah et al., 2023), with sub-switches for a low willingness variant and for a traditional diffusion variant that seeds innovators at fixed geographic centers. Mode B exists so that the model can be transferred to a site where no farm level data are available for estimating thresholds. All results in this deliverable use Mode A.

3.2 Input data

Table 2: Input data sets.

Data set	Content	Level
Field register	Crop code per field and year, field geometry, area	Field, annual
Farm register	Farm identity, managed fields, livestock units, amount of organic fertiliser use	Farm
Soil and nitrogen layer	Soil carbon, nitrogen retention rate, baseline nitrogen leaching	Field
Facility register	Location and type of biogas plants and planned biorefinery sites	Geographic point
Parish boundaries	Polygon geometry, adjacency	Parish
Road distance matrix	Road distances from each field to each biogas plant; straight line distances to biorefinery candidate sites.	Field × facility
Crop economics	Yields, prices, variable costs 2008 to 2023	Regional, annual
Probit output	Segment counts and propensity scores per parish × rotation × segment	Parish × rotation

The baseline nitrogen load[1] layer is the business-as-usual allocation produced by the decision support tool of D3.5 (Frick et al., 2026). Land use change in ADAPtES is generated by the adoption decisions of the agents, so the model needs the baseline against which the change is measured, not a prescribed target allocation.

All input data are static. Nothing is read during a run; every temporal change is generated by the model.

[1] Note that the nitrogen load is defined as.....

3.3 Submodels

3.3.1 Land suitability

A field-agent becomes eligible only if it meets all of the following criteria:

- the field is arable, that is, its crop category is not ‘take-out’ and not ‘other’;
- the observed seven-year crop sequence matches one of the three reference rotations described in Section 3.3.3;
- the last recorded year is not a set-aside year; which means if the last year of the 7yr rotation is fallow land, the field is not considered.
- the field is not under permanent grassland or an orchard.

The aggregation of the 423 register crop codes into the eleven crop categories used for this test is given in Annex A-5 of the working report (Möhring et al., 2026). Of 57,422 fields, 23,111 satisfy the conditions. Ineligible fields remain in the model, retain their baseline nitrogen-leaching values and contribute to the landscape nitrogen balance, but cannot adopt.

3.3.2 Processing access and facility activation

Reach. Let d_R and d_G be the straight-line distance from a field to the nearest candidate biorefinery site and the road distance to the nearest biogas plant, and r_R and r_G the corresponding trading radii.

In the biogas only configuration a field is accessible if the road distance to the nearest biogas plant is within the biogas radius:

$$d_G \leq r_G$$

In the biorefinery configuration a field is accessible if the straight-line distance to the nearest candidate biorefinery site is within the biorefinery radius:

$$d_{\mathrm{R}} \leq r_{\mathrm{R}}$$

Candidate biorefinery sites are existing biogas sites. Biogas plants do not confer eligibility in the biorefinery configuration because they process residues returned from the biorefinery and are not an outlet for grass. The candidate site, rather than the active one, defines the zone, so that latent demand can build up around a site that has not yet opened. This is important because biorefineries do not exist at the starting point (t = 0, where t denotes a four-year period) and open endogenously. A farmer making decisions in period (t) therefore cannot know which site, if any, will eventually serve the field.

Because biorefineries are built on existing biogas sites, the distance that enters the transport cost is, in both configurations, the road distance to the nearest biogas plant (d_G). It is exact whenever the nearest biogas site hosts the biorefinery that serves the field and understates the cost otherwise. The same distance is used when the farmer evaluates the conversion and when the contract is signed, so willingness and delivery are priced consistently.

Supply of a field. Not all grass is delivered. A share is retained on the farm as feed, as the existing livestock supply chain remains intact. With a the field area, α the allocation share of the field to grass, δ the delivered share and Y the grass dry matter yield of the period,

$$s = a * \alpha * \delta * Y \qquad [t\ DM\ per\ year]$$

with $\delta = 0.80\ and\ \alpha = 1$ in all scenarios reported here.

Units. The model tracks biomass in dry matter. The capacity parameters were specified by the site partners as fresh matter throughput. Both are converted once at initialisation using a dry matter content of 18 %:

$$K_{DM} = K_{FM} * 0.18$$

The same conversion is applied to the minimum viable supply of a biorefinery and to the minimum and maximum intake of a biogas plant. All subsequent comparisons are made in dry matter.

Activation. Biorefinery sites are inactive at (t) = 0. In each period, the model computes, for every inactive site, the supply that could be claimed from "willing" fields within its radius, excluding fields already within the radius of an active site. The site with the largest claimable supply is activated if that supply reaches the minimum viable supply S_{min}. At most one site is activated per period. The exclusion rule prevents a second plant from being justified by demand an existing plant already covers, which keeps activated plants spread across the region rather than clustered on one supply pool. The number of biorefineries cannot exceed the number of existing biogas sites, because the partners assume a biorefinery is built at an existing biogas location.

Capacity. Each active biorefinery has a remaining capacity that is refilled to K_{DM} at the start of every period and drawn down as fields are allocated. A field of a willing farm agent that finds no free slot within reach remains willing and is recorded as latent demand. It does not exit; it waits.

Processing capacity is booked at the planning yield, the mean of the yield distribution (11.86 t DM per hectare), when a supplier is admitted and held for the term of the contract and on renewal. In a period of above-average yield the plant takes delivery of the contracted fields' full output but processes at most its capacity; the surplus is reported separately and is neither processed nor fed.

The energy crop cap. Under Danish law, whole crop grass delivered to a biogas plant is classified as an energy crop and is capped at 4 % of the plant's total input weight. A 12 % allowance is permitted on the first 36,000 tonnes (Klima-, Energi- og Forsyningsministeriet, 2025). This results in a total capacity utilisation of 6,188 tonnes of fresh matter grass per plant per year, which is considered in the baseline scenario (S0a).

The cap is implemented as the maximum grass intake of a biogas plant. In the biorefinery configuration the biogas plant is not a direct outlet for grass: it digests the fibre and brown juice returned from the biorefinery, which are processing residues and not subject to the cap.

3.3.3 Profit

Reference crop rotations. Three reference rotations were derived from the observed seven-year sequences: a cereal rotation, a maize and cereal rotation, and a potato and cereal rotation. Each seven-year crop sequence is compressed to the four-year period of one model step by taking the three observed years and, for the fourth position, the mean gross margin of years four to seven. That fourth term is field specific: it is read from a table keyed by parish and rotation, so it takes up to 1,248 distinct values across the region.

Profit of the reference rotation. For period t, with n = 0, …, 3 the years of the period,

$$P_T(t) = \sum_n NP^{4t+n} * G_n$$

where G_n is the gross margin of the crop in position n of the rotation and NP = 1/(1+ρ) is the discount multiplier with ρ = 0.04 the real discount rate. At t = 0 the G_n are deterministic and equal to the mean deflated gross margins of 2008 to 2023 (Table 7). From t = 1 onwards each G_n is drawn once per period from a normal distribution fitted to the annual series 2008 to 2023 (Seges Innovation, 2026; StatBank Denmark, 2026). All prices and variable costs are deflated to the 2023 price level before the distributions are fitted, year by year: prices with the index of agricultural sales prices and variable costs with the index of agricultural purchase prices of StatBank Denmark (tables LPRIS20, LPRIS21 and LPRIS22). The gross margins are therefore expressed in real terms at 2023 prices. The fourth term is the field specific mean gross margin of years four to seven in every period.

Profit of the grass rotation. The grass rotation occupies all four years of the period. Its annual margin is

$$g = e \cdot \left[\beta_{\mathrm{R}} \Pi_{\mathrm{R}} + \beta_{\mathrm{G}} \Pi_{\mathrm{G}} + \beta_{\mathrm{R}} \frac{b}{100} R_{\mathrm{prot}} - C\right] + I \qquad [\mathrm{EUR\ ha^{-1}\ yr^{-1}}]$$

where Π_{R} and Π_{G} are the margins from delivering to a biorefinery and to a biogas plant, β_{R} and β_{G} indicator variables that select the configuration (β_{R} = 1, β_{G} = 0 in the biorefinery configuration; the reverse in the biogas-only configuration), R_{prot} the revenue from the delivered products, b an optional bonus on that revenue in per cent (b = 0 in all runs), C the transport cost per hectare (see below), e = 0.1345 EUR per DKK the exchange rate and I the area payment in EUR per hectare and year. Π_{R}, Π_{G}, R_{prot} and C are in DKK per hectare and year. The discounted profit of the grass rotation is

$$P_B(t) = \sum_n NP^{4t+n} * g$$

The two component margins are

$$\Pi_{\mathrm{R}} = Y \cdot \delta \cdot \left(\kappa \cdot v_{\mathrm{R}} - c_{\mathrm{g}}\right) \qquad [\mathrm{DKK\ ha^{-1}\ yr^{-1}}]$$

$$\Pi_{\mathrm{G}} = Y \cdot \delta \cdot \left(\kappa \cdot v_{\mathrm{G}} - c_{\mathrm{g}}\right) \qquad [\mathrm{DKK\ ha^{-1}\ yr^{-1}}]$$

where Y is the grass dry matter yield in t DM per hectare and year, δ = 0.80 the delivered share, c_{g} the cost of growing and harvesting the grass in DKK per t DM, drawn from N(790, 60) (Strunge Folkmann, 2024), and κ = 1 − s/100 the share of the product value passed to the farmer, with s the processor share in per cent. In all runs reported here s = 0, so the farmer receives the full value of the products and processing is not charged. The harvest is contained in c_{g} and is not charged separately. The 20 % of the yield retained on the farm is valued at its production cost and therefore adds no margin; revenue and cost are counted on the delivered share only. v_{R} and v_{G} are the product values per tonne of dry matter delivered:

$$v_{\mathrm{R}} = f_{\mathrm{prot}} \cdot s_{\mathrm{CP}} \cdot 1000 \cdot p_{\mathrm{prot}} + f_{\mathrm{fib}} \cdot 1000 \cdot p_{\mathrm{fib}} \qquad [\mathrm{DKK\ (t\ DM)^{-1}}]$$

$$v_{\mathrm{G}} = y_{\mathrm{CH4}} \cdot p_{\mathrm{CH4}} \qquad [\mathrm{DKK\ (t\ DM)^{-1}}]$$

with f_{prot} = 0.182 and f_{fib} = 0.586 the shares of grass dry matter that end up in the protein concentrate and in the fibre (derived from the mass balance below), s_{CP} = 0.40 the crude protein share of the concentrate, p_{prot} = 14.30 DKK per kg crude protein (Strunge Folkmann, 2024), p_{fib} = 0.88 DKK per kg DM, y_{CH4} = 2.40 MWh per t DM and p_{CH4} = 597.92 DKK per MWh. This gives v_{R} ≈ 1,557 and v_{G} ≈ 1,435 DKK per t DM. The revenue on which the bonus b is calculated is $R_{\mathrm{prot}} = Y \cdot \delta \cdot \kappa \cdot v_{\mathrm{R}}$.

Transport cost. Transport is charged to the farmer and enters the grass margin as a cost per hectare. It has a component incurred once per load, independent of distance, and a component proportional to distance. With Y the grass dry matter yield in t DM per hectare of the period, δ the delivered share and w the dry matter content of fresh grass, the fresh matter leaving one hectare is $\frac{Y*\delta}{w}$, and where h is the handling rate in DKK per tonne, k the road rate in DKK per tonne and kilometre, and d the haul distance in kilometres. The cost of hauling is:

$$C = (h + k * d) * \frac{Y * \delta}{w}$$

The two rates follow the arithmetic of the Danish harvest and transport study [(Kjeldal, 2023), p.16]. With H the hourly rate of the vehicle and driver, m the handling time per load in minutes, L the load in tonnes and v the average road speed:

$$h = (H/60) * \frac{m}{L} \qquad [DKK\ per\ tonne]$$

$$k = 2 * \frac{H}{v * L} \qquad [DKK\ per\ tonne\ and\ kilometre]$$

The factor two in k accounts for the empty return leg in full. The base configuration uses the tractor-and-trailer case of that study: H = 800 DKK per hour, L = 18 t, v = 40 km per hour and a filling time of 20 minutes, giving h = 14.81 DKK per tonne and k = 2.22 DKK per tonne and kilometre. The sensitivity run *SENS_transport_lorry* uses the lorry case of the same source: H = 800, L = 30 t, v = 50 km per hour and 10 minutes of filling, emptying and access, giving h = 4.44 and k = 1.07. Both parameter sets are written to the output file for every run.

The two rates are model parameters and are written to the output file of every run, so the values behind any reported result can be read from the run metadata.

The cost is computed once, at the moment a field signs a contract, and is then held fixed for the term of the contract. The reported transport cost is therefore the cost agreed at signature and not the cost of the current period. Three simplifications work in the same direction and make the figure conservative: one vehicle type serves all distances, the return leg is charged in full, and the handling time per load does not fall with field size.

The decision variable is calculated as follows:

$$\Delta P(t) = P_B(t) - P_T(t)$$

Yield. The grass dry matter yield Y is drawn once per period from N(11.86, 2.12) t DM per hectare and applies to the whole landscape in that period. This is a simplification: it removes cross-sectional variation in grass yield while retaining temporal variation. Its consequence for the analysis is set out in Section 2.9.

3.3.4 Diffusion and the adoption threshold

The social signal. For each field, let N be the set of fields in the own parish and in adjacent parishes that are accessible to a processor, excluding the field itself. The signal is the net share of willing neighbours weighted by the sign of their profit difference:

$$AR = \frac{(\,|\{i \in N : willing_i \; and \; \Delta P_i > 0\}| - |\{i \in N : willing_i \; and \; \Delta P_i < 0\}|\,)}{|N|}$$

so, AR ∈ [−1, 1].

The signal is negative when willing neighbours are making a loss, which allows the diffusion process to reverse. The signal counts field-agents that have decided, not field-agents that are delivering, so a farmer who wants to convert but has found no outlet still transmits a positive signal.

The threshold. Each field is assigned an adoption threshold AT ∈ [0, 1], and a propensity score derived from a probabilistic estimation. In Mode A, the propensity score is obtained from a probit model estimated on the regional farm population.

The dependent variable is whether the farm operates a complex rotation, defined, following (Jänicke et al., 2022; Stein and Steinmann, 2018), as three or more different crops in a seven-year period on the same field including a legume, on more than 50 % of the utilised agricultural area. Fields under permanent grass and orchards are excluded from the test. The choice of a complex rotation as the proxy for innovativeness rests on the argument that the practice under study is itself a rotation change, so past willingness to diversify a rotation is the closest observable analogue (Grovermann et al., 2017). Legumes are counted at the level of the aggregate crop category, which includes clover grown for seed. Three alternatives were considered and rejected: farms already delivering grass to a biogas plant or a biorefinery, which are too few for estimation; organic farms, which would conflate a certification decision with a rotation decision; and a combination of the two. The definition treats three crops in seven years as complex, whereas other studies classify such a sequence as moderately complex, and it ignores the order of the crops.

The predictors are the number of fields on the farm, the mean field size, the mean soil carbon content, the soil nitrogen retention, three livestock density classes and three organic fertiliser use classes. The probit model is estimated on 2,391 farms with robust standard errors clustered at municipality level (McFadden pseudo R^2 = 0.238; area under the ROC curve = 0.818). Larger farms and farms using organic fertiliser are more likely to operate a complex rotation; farms holding livestock, and farms on soils with higher carbon content or higher nitrogen retention, are less likely to. The estimates are reported in the working report (Möhring et al., 2026).

The estimated propensity scores rank the farms, and the ranking is divided at the thresholds of diffusion theory into five adopter categories: innovators (2.5 %), early adopters (13.5 %),

early majority (34 %), late majority (34 %) and laggards (16 %) (Rogers, 2003). The probit therefore serves one purpose: it decides which segment a farm belongs to. It does not set the value of the threshold.

The threshold itself is the cumulative share of all preceding segments, following Grovermann et al. (2017):

Table 3: Adoption thresholds by adopter category.

Category	**Farms** (total 2,391)	**Share of farms**	**Adoption threshold AT**
Innovators	60	2.5 %	0
Early adopters	323	13.5 %	0.025
Early majority	812	34 %	0.16
Late majority	813	34 %	0.50
Laggards	383	16 %	0.84

A farm of the early majority therefore converts once the signal in its neighbourhood reaches the share that innovators and early adopters together represent. Innovators carry a threshold of zero and start the process wherever the grass rotation is profitable. Because the segment is a farm attribute, all fields of a farm share the same threshold; because the threshold is a function of the segment alone, it does not vary between parishes. The model reads the assignment from a lookup table that gives, for each parish and reference rotation, the number of fields in each adopter category. Fields are allocated to the categories at random within each parish and rotation cell in these proportions, and farm identities are then attached within the same parish, rotation and category, so that all fields of a farm carry the category of that farm. The simulation uses the discrete category, not the continuous propensity score, because the five categories reproduce the S-shaped diffusion curve, whereas a continuous threshold spread over the whole population produces a smoother and flatter path.

Comparing AR with a cumulative population share is an operationalisation, not an identity. AR as defined above is a net signal that falls when willing neighbours are making a loss, so the effective barrier is somewhat stricter than the Rogers share it is compared with.

3.3.5 Contracts

A field-agent that becomes willing and obtains a delivery slot signs a contract. Contracts run for eight years, that is two periods. At expiry the model recomputes the profit difference at the distance to the plant the field-agent is committed to, and renews the contract if the grass rotation is still profitable and the plant is still reachable; otherwise the field-agent releases its slot and reverts to the reference rotation. Two alternative regimes are available for sensitivity

analysis: permanent contracts, which never expire, and irreversible adoption, under which a field that has adopted stays under grass regardless of profitability.

Contract expiry is synchronous for fields that adopted in the same period, so the model produces cohort effects: a wave of adoption in one period generates a wave of renewal decisions two periods later. The timing of the resulting exits varies between replications and is visible only in individual runs, not in the ensemble median (see Figure 3 of the policy brief).

3.3.6 Mass balance of the processing chain

The fractionation follows the process description of the Danish reference plant (Termansen et al., 2016). Let F be the fresh matter delivered to biorefineries in a period, F = D / 0.18 with D the delivered dry matter. The three fractions are

Fraction	**Share of fresh matter**	**Dry matter content**
Fibre	39 / 111	30 %
Protein concentrate	13 / 111	28 %
Brown juice	59 / 111	8 %

Crude protein in the concentrate is 40 % of its dry matter, and nitrogen is crude protein divided by 6.25.

Methane energy is computed from the dry matter of each digested fraction:

$$E = 2.85 * M_{fibre} + 3.48 * M_{juice} + 2.40 * M_{wholecrop} \qquad [MWh]$$

with the coefficients in MWh per tonne of dry matter. The fibre coefficient is taken from Ravindran et al. (2022) for grass press cake, the brown juice coefficient from the Danish process description and the whole crop coefficient is the parameter already used in the biogas profit path. Two sources are needed because the Danish description reports no methane yield for the fibre fraction, which is treated as feed in that source. The model assumes no livestock and therefore the fibre fraction as available for digestion.

Total nitrogen in the digested streams is derived from the crude protein content of each fraction, 17 % of dry matter for fibre, 4 % for brown juice and 20 % for whole crop grass:

$$N_{dig} = \frac{\left(0.17 * M_{fibre} + 0.04 * M_{juice} + 0.20 * M_{wholecrop}\right)}{6.25} \qquad [t\ N]$$

This is total nitrogen, not plant-available nitrogen.

3.3.7 Nitrogen accounting

For each field, baseline leaching L_{BAU} is drawn at initialisation step from the DST calculation (Frick et al., 2026). Leaching under the grass rotation is derived from the nitrogen retention of the cell:

$$L_{grass} = 25 * (100 - RET)/100 \qquad [kg\ N\ per\ hectare\ and\ year]$$

where RET is drawn per field from the parish × rotation retention distribution. L_{grass} is clamped to non-negative values. The coefficient of 25 kg N per hectare is the mean of the four site-years reported by (Fontaine et al., 2024) for a grass-clover ley fertilised at 200 kg N per hectare, the same treatment from which the grass yield distribution of Section 3.3.3 is taken.

For a field with grass area $a_g = a * \alpha$ when the field delivers and zero otherwise, the annual reduction is

$$\Delta N = L_{BAU} * a - \left(L_{grass} * a_g + L_{BAU} * \left(a - a_g\right)\right)$$

The reduction accrues to delivering fields only. A field whose farm agent is willing but has no outlet grows no grass and keeps its baseline leaching. Annual reductions are multiplied by four to obtain period value and then accumulated over the simulation horizon.

3.4 Model outputs

One record per period and replication carries 51 fields, covering the adoption state, the facility state, the mass balance, the energy and nutrient indicators, the profit and payment indicators, and the nitrogen balance. Cost effectiveness is computed after the run as the discounted public expenditure divided by the cumulative nitrogen reduction.

3.5 Parameters

Parameters are given in the unit in which they enter the model. Monetary values are in Danish kroner (DKK) and are converted at 0.1345 EUR per DKK for reporting. Values in brackets are the settings of the sensitivity runs.

Table 4: Grass yield and fractionation.

Parameter	Symbol in code	Value	Unit	Source
Grass dry matter yield	YieldGrassDM	N(11.86, 2.12)	t DM ha^{-1} yr^{-1}	(Fontaine et al., 2024); drawn once per period
Planning yield for capacity booking	yield-grass-expected	11.86	t DM ha^{-1} yr^{-1}	Mean of the yield distribution
Dry matter content of fresh grass	grass-DM-content	0.18	share	(Bojesen et al., 2016)
Delivered share of the harvest	grass-deliver-share	0.80	share	(Strunge Folkmann, 2024)
Share of the field allocated to grass	default-allocation-share	1.00	share	Scenario assumption

Parameter	Symbol in code	Value	Unit	Source
Protein concentrate, share of grass DM	frac-protein-dm	0.182	share of DM	Derived from Termansen et al. (2016)
Fibre, share of grass DM	frac-fibre-dm	0.586	share of DM	Derived from Termansen et al. (2016)
Brown juice, share of grass DM	–	0.236	share of DM	Derived from Termansen et al. (2016)
Crude protein in the protein concentrate	ShareCrudeProteinYield	0.40	share of DM	Strunge Folkmann (2024)
Methane yield, whole crop grass	YieldBiogas	2.40	MWh t DM^{-1}	Strunge Folkmann (2024)
Methane yield, fibre	CH4-fibre-MWh-per-tDM	2.85	MWh t DM^{-1}	Ravindran et al. (2022)
Methane yield, brown juice	CH4-residue-MWh-per-tDM	3.48	MWh t DM^{-1}	Termansen et al. (2016)

Note: The dry matter shares of the three fractions follow from the fresh matter shares and dry matter contents of the mass balance (Section "Mass balance of the processing chain"), so the profit calculation and the mass balance use the same fractionation.

Table 5: Prices and costs of the grass chain.

Parameter	Symbol in code	Value	Unit	Source
Protein price	Refinery_Grass_Protein_Price	14.30 (1.92 EUR)	DKK kg^{-1} crude protein	Strunge Folkmann (2024)
Fibre price	Refinery_Grass_Fibre_Price	0.88	DKK kg^{-1} DM	Strunge Folkmann (2024)
Biomethane price	Biomethane_Price	597.92	DKK MWh^{-1}	The biomethane price is taken as reported in Strunge Folkmann (2024)
Growing and harvest cost	Refinery_Grass_Cost	N(790, 60)	DKK t DM^{-1}	Strunge Folkmann (2024): 0.67 DKK kg^{-1} DM on the root plus 0.12 for harvest
Processor share of the product value	processor-share	0	%	Scenario setting; 0 = no processing charge
Handling rate, transport	handling-DKK-per-t	14.81 (lorry: 4.44)	DKK t^{-1} FM	Derived from Kjeldal (2023)

Parameter	Symbol in code	Value	Unit	Source
Road haulage rate	road-DKK-per-tkm	2.22 (lorry: 1.07)	DKK t^{-1} FM km^{-1}	Derived from Kjeldal (2023)
Exchange rate	DKKtoEuro	0.1345	EUR DKK^{-1}	Annual average
Real discount rate	ρ, with NP = 1/(1+ρ)	0.04	yr^{-1}	(Michaelides, 2024; Upadhaya and Dwivedi, 2019)

Note: The protein price assumes that one quarter of the protein is sold as white protein at the value of milk protein and three quarters as green protein at the value of soybean meal.

Table 6: Distributions from which yield, price and variable cost of the reference crops are drawn once per period. Mean with standard deviation in brackets. Statistics Denmark, 2008 to 2023, deflated to 2023 prices.

Crop	Yield	Unit	Price	Unit	Variable cost [DKK ha^{-1}]	Gross margin at the mean [DKK ha^{-1}]
Cereal, winter	76.94 (6.72)	hkg ha^{-1}	183.5 (26.11)	DKK hkg^{-1}	5,904.31 (495.336)	8,214
Cereal, spring	56.38 (6.15)	hkg ha^{-1}	192.14 (28.25)	DKK hkg^{-1}	4,725.75 (417.71)	6,106
Maize	10,302.88 (866.55)	FE ha^{-1}	1.31 (0.13)	DKK FE^{-1}	8,442.94 (1,629.09)	5,054
Potato	446.38 (17.74)	hkg ha^{-1}	71.81 (23.07)	DKK hkg^{-1}	19,795.5 (1,943.37)	12,259

Note: The gross margin of a crop in a given period is drawn as yield times price less variable cost, so the three draws are independent and the resulting margin carries the combined variance. FE: feed units (foderenheder).

Table 7: Gross margins used at t = 0, mean of the deflated annual gross margins 2008 to 2023, DKK ha^{-1} at 2023 prices.

Crop	Mean (2008 to 2023)
Cereal, winter	8,179
Cereal, spring	6,125
Maize	5,045
Potato	12,515

Note: The gross margins used at t = 0 lie within about 2 % of the gross margins at the means of the distributions in Table 6.

Table 8: Processing.

Parameter	Symbol in code	Value	Unit	Source
Biorefinery intake capacity	bioref-capacity-tons	216,000 (139,000; 432,000)	t FM yr^{-1}	Site partners: 60 t h^{-1} × 20 h d^{-1} × 180 d yr^{-1}
Minimum viable supply, biorefinery	bioref-min-supply-tons	20,000 (10,000; 40,000)	t FM yr^{-1}	Site partners
Minimum grass intake, biogas plant	biogas-min-supply-tons	1,000	t FM yr^{-1}	Assumption
Maximum grass intake, biogas plant	biogas-max-supply-tons	6,188 (cap in force); 82,700 (cap removed)	t FM yr^{-1}	Klima-, Energi- og Forsyningsministeriet (2025)
Existing biogas plants, which are also the candidate biorefinery sites	–	55	number	Facility register
Crude protein content of fibre / brown juice / whole crop grass	–	0.17 / 0.04 / 0.20	share of DM	Termansen et al. (2016)
Nitrogen from crude protein	–	crude protein / 6.25	–	Standard conversion

Table 9: Behaviour, contracts, space and time.

Parameter	Symbol in code	Value	Unit	Source
Threshold mode	use-probit?	true (Mode A)	–	Section “Diffusion and the adoption threshold”

Parameter	Symbol in code	Value	Unit	Source
Adoption thresholds	–	0 / 0.025 / 0.16 / 0.50 / 0.84	share	Rogers (2003); Grovermann et al. (2017)
Contract mode	contract-mode	fixed-term (permanent)	–	Stakeholder workshop, May 2026
Contract duration	contract-duration-years	8	yr	Site partners
Reversibility	adoption-reversibility	reversible	–	Stakeholder session, April 2026
Trading radius, biorefinery	bioref-radius-size	5 / 10 / 20	km	Site partners; Bojesen et al. (2016)
Trading radius, biogas	biogas-radius-size	20	km	Site partners
Number of parishes	–	416	number	Parish boundaries
Time step	–	4	yr	Grass period, Klimafonden Skive (2025)
Simulated horizon	sim-horizon	6, i.e. t = 0 to 6 (28 years)	steps	–
Replications	–	100 (30 for the minimum supply and first plant runs)	runs	–

Table 10: Nitrogen.

Parameter	Value	Unit	Source
Leaching below the root zone under grass	25	kg N ha^{-1} yr^{-1}	Fontaine et al. (2024)
Load under the reference rotation	per parish and rotation	kg N ha^{-1} yr^{-1}	Decision support tool of WP3 (Deliverable D3.5)
Nitrogen retention	32.3 to 99.8, per sub-catchment	%	(Højberg et al., 2026)

Table 11: Policy levers and sensitivity settings.

Parameter	Symbol in code	Levels
Area payment	Refinery_Grass_Incentive	0, 100, 200 EUR ha^{-1} yr^{-1}
Protein bonus	Refinery_Grass_Bonus	0 % in all runs

Parameter	Symbol in code	Levels
Processor share	processor-share	0 % in all runs reported in the policy brief
Processing route	processor-mode	biogas only; biorefinery and biogas
Energy crop cap	biogas-max-supply-tons	in force (6,188 t FM) or removed (82,700 t FM)
Sensitivity runs at 20 km and 200 EUR ha^{-1}	–	capacity 139,000 or 432,000 t FM; lorry haulage rates; permanent contracts; minimum supply 10,000 or 40,000 t FM; first plant at site 4 or 25

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