

WATER-PROFIT DECOUPLING: AGROECOLOGICAL TRANSITION IN CAP BON

DÉCOUPLAGE EAU-BENEFICE: TRANSITION AGROÉCOLOGIQUE AU CAP BON

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ABSTRACT

Mediterranean agriculture is reaching a structural threshold under sustained drought. The dominant adaptation responses — improved drip uniformity, mulching, deficit irrigation — concentrate on the efficiency of water application within existing perennial production systems. These responses remain necessary, but where the binding constraint becomes absolute water availability rather than application efficiency, a complementary lever emerges: a *traditional-to-adaptive transition* that replaces a water-intensive value chain with a climate-adapted one. This paper develops a biosystem microsimulation to ask whether, on a documented Mediterranean farm where the established citrus value chain has failed, a transition to an olive–aloe vera value chain managed under agroecological practices — manual weed control, on-farm compost, biocontrol, no synthetic fertiliser — can decouple water demand from long-term profitability while improving environmental outcomes.

The microsimulation is calibrated on a 7-hectare smallholding in Cap Bon, Tunisia, where the orange grove (6 800 m³/ha/yr irrigation demand) failed in 2023 and was replaced in 2025 with an olive–aloe vera intercrop. The model integrates a six-stage pipeline — input, pre-processing, deterministic year-by-year modelling, economic calculation, four-pool carbon accounting, scenario analysis — over 2015–2054, driven by observed climate and CMIP6 SSP2-4.5 projections.

Three convergent paybacks emerge. **Water decoupling is immediate:** whole-farm demand falls 91 percent, and water intensity per unit of revenue falls 72-fold (from 2 900–10 800 to ~41 m³/k€).¹ **Carbon payback occurs in year 5** (2030, +187 t CO₂e cumulative by 2054). **Economic payback occurs in year 9** (2034, +€256k cumulative cash flow over the no-transition counterfactual). The value-chain transition alone — even under conventional management — closes a €388k gap; the agroecological management layer adds a further €244k. Monetary and environmental profitability are achieved together. Economic figures reflect raw aloe leaf sales — a conservative lower bound; downstream gel processing, to be modelled in future work, would raise farm-gate value substantially.

Keywords: traditional-to-adaptive transition; value-chain transition; agroecological transition; water-profit decoupling; biosystem microsimulation; Mediterranean drought; Cap Bon.¹ Original calculations in Tunisian Dinar (TND); EUR figures use a reference exchange rate of 3.4 TND ≈ €1 (rough mid-2025 average).

RESUME

L'agriculture méditerranéenne arrive à un seuil structurel sous l'effet de sécheresses persistantes. Les réponses d'adaptation dominantes — amélioration de l'uniformité goutte-à-goutte, paillage, irrigation déficitaire — se concentrent sur l'efficacité de l'application de l'eau au sein des systèmes de production pérennes existants. Ces réponses restent nécessaires, mais là où la contrainte contraignante devient la disponibilité absolue de l'eau plutôt que son efficacité d'application, un levier complémentaire

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émerge : une transition vers un modèle adaptatif qui remplace une chaîne de valeur intensive en eau par une chaîne adaptée au climat. Cet article développe une microsimulation de biosystèmes pour demander si, dans une ferme méditerranéenne documentée où la chaîne de valeur des agrumes établie a échoué, une transition vers une chaîne de valeur olive–aloe vera gérée selon des pratiques agroécologiques — contrôle manuel des mauvaises herbes, compost à la ferme, biocontrôle, absence d'engrais de synthèse — permet de dissocier la demande en eau de la rentabilité à long terme, tout en améliorant les résultats environnementaux.

La microsimulation est calibrée sur une petite exploitation de 7 hectares à Cap Bon, en Tunisie, où l'orangerie (besoin en irrigation de 6 800 m³/ha/an) a échoué en 2023 et a été remplacé en 2025 par une culture mixte d'olive–aloe vera. Le modèle intègre un processus en six étapes — intrants, prétraitement, modélisation déterministe annuelle, calcul économique, comptabilité du carbone à quatre réservoirs, analyse de scénarios — couvrant la période de 2015-2054, basé sur les données climatiques observées et les projections CMIP6 SSP2-4.5. Trois retours convergents émergent. Le **découplage de l'eau est immédiat** : la demande globale de l'exploitation agricole chute de 91%, et l'intensité hydrique par unité de revenu tombe de 72 fois (passant de 2 900–10 800 à ~41 m³/k€).¹ Le **retour du carbone se trouve en 5^{ème} année** (2030, +187 t CO₂e cumulé d'ici 2054). Le **retour économique survient en 9^{ème} année** (2034, +256 000 € de cash-flow cumulé par rapport au scénario de l'hypothèse sans transition). La transition de la chaîne de valeur à elle seule — même dans le cadre d'une gestion conventionnelle — comble un écart de 388000 €; la couche de gestion agroécologique ajoute 244k € supplémentaires. La rentabilité monétaire et environnementale est réalisée ensemble. Les chiffres économiques reflètent les ventes de feuilles d'aloès brutes — une limite inférieure prudente ; le traitement du gel en aval, à modéliser dans des travaux futurs, augmenterait considérablement la valeur totale à la ferme.

Mots-clés : Transition du modèle traditionnel vers un modèle adaptatif; Transition de la chaîne de valeur; Transition agroécologique; Découplage eau et bénéfice; Microsimulation des biosystèmes; Sécheresse en Méditerranée; Cap Bon. 1 Calculs initiaux en dinars tunisiens (TND); les montants en EUR utilisent un taux de change de référence de 3,4 TND ≈ 1 € (moyenne approximative prévue pour la mi-2025).

1. INTRODUCTION

Mediterranean perennial agriculture has reached a structural threshold under sustained drought. In Tunisia, agriculture absorbs approximately 74 percent of national water use, and seven consecutive years of below-average rainfall have driven aquifer levels and dam reserves below operational thresholds across the Cap Bon citrus belt. The conventional adaptation response within the irrigation engineering community has been to improve the *efficiency of water application*: drip in place of furrow, deficit irrigation, mulching, soil moisture sensors. This response is necessary but, in the limit, insufficient. When a citrus orchard requires 6 800 m³ per hectare per year for full evapotranspiration replacement and the local well delivers 0 — as documented on the case-study farm in 2023 — no improvement in *how* water is applied can rescue the system. The binding constraint is the crop's absolute demand.

This paper proposes and quantifies a *traditional-to-adaptive transition*: where the binding constraint is absolute water availability rather than application efficiency, the adaptation lever shifts from incremental irrigation efficiency to a structural reconfiguration of the production value chain. The physical foundation rests on plant water-use physiology. Citrus is a C3 species with no effective stomatal regulation; transpiration scales directly with potential evapotranspiration. Olive (*Olea europaea*), also C3 but with strong osmotic stomatal regulation, sustains yield on a small fraction of the water citrus requires. Aloe vera (*Aloe barbadensis*) is a Crassulacean Acid Metabolism (CAM) succulent: night-opening stomata reduce transpiration losses by an order of magnitude relative to C3 crops. The water-demand differential — 6 800, 108, and 490 m³ per hectare per year — is what makes the transition feasible.

The literature documents this physiological gradient (Sofa et al., 2005; Singh et al., 2021) and reports irrigation-engineering responses to Mediterranean drought (Fernandez et al., 2018), but no published

microsimulation has jointly tracked water, profit and carbon over a 30-year horizon for a documented value-chain transition on a single Mediterranean farm under a CMIP6 climate trajectory. Agronomic studies of olive intercropping report short-horizon Land Equivalent Ratios (Amassaghrou et al., 2023; Bilali et al., 2024) without economic dynamics; afforestation microsimulations such as AFFOR (Ryan et al., 2025) integrate carbon and economics but for land-use change rather than agricultural value-chain transition. This paper closes the gap. Section 2 sets out the framework, Section 3 the case-study farm and data, Section 4 the methodology, Section 5 the results, Section 6 the discussion, Section 7 the next steps, Section 8 the conclusion.

The methodological lineage. The microsimulation tradition in agricultural economics is structured around the linkage of micro-data to deterministic accounting cores extended with stochastic and scenario layers (O'Donoghue, 2014). National-scale agricultural microsimulations have demonstrated the value of this architecture for ex-ante policy assessment of land-use change — most recently the AFFOR national afforestation model (Ryan, Kilcline and O'Donoghue, 2025), which integrates carbon, economics and a Chapman-Richards biomass curve across a representative national farm sample. This paper develops a *single-farm biosystem variant* of that architecture for a different policy object: not land-use change, but a structural reconfiguration of an agricultural value chain on the same hectare under sustained drought. The single-farm calibration trades scale for resolution — eleven years of plot-level observation, a documented switch event, a thirty-year projection horizon — and is by design the unit cell from which a regional Cap Bon microsimulation could be assembled. The framework borrows AFFOR's four-pool carbon structure and Chapman-Richards parameterisation, adapts the economic layer to a perennial value-chain transition rather than an afforestation event, and adds a value-chain isolation step (Section 5.5) absent from land-use models because it has no analogue in afforestation. The contribution is therefore both substantive (the water-profit decoupling result) and methodological (a single-farm value-chain-transition microsimulation, extending the AFFOR lineage to the Mediterranean perennial-adaptation problem).

2. THEORETICAL FRAMEWORK: FROM A TRADITIONAL VALUE CHAIN TO A CLIMATE-ADAPTED ONE

The paper frames Mediterranean climate adaptation as a *traditional-to-adaptive transition*: not the substitution of one plant for another, but the replacement of an entire production value chain whose inputs, on-field practices, downstream processing and market positioning have all become incompatible with the regional water budget. The conventional Cap Bon citrus value chain rests on a high-water-input crop irrigated at close to potential evapotranspiration, supported by synthetic fertiliser and conventional pesticide, mechanically cultivated for weed control, and supplying a price-pressured commodity export market. The climate-adapted value chain quantified here pairs two drought-resilient species — olive with strong osmotic stomatal regulation, and aloe vera, whose night-opening CAM stomata reduce transpiration by an order of magnitude relative to C3 crops — under agroecological management, supplying differentiated organic markets with downstream-processing potential. Figure 1 shows the steady-state irrigation demand of the three crops alongside their photosynthetic pathway.

The transition affects every node of the value chain. **Upstream**, irrigation infrastructure shifts from continuous full-ET drip drawing on an over-stressed shallow well to a deeper borehole serving a winter-runoff storage bassin; synthetic NPK fertilisers are replaced by on-farm compost from pruning residues; conventional pesticide and chemical herbicide are replaced by biocontrol and manual desherbage. **On the farm**, the labour profile changes materially: input cost falls while seasonal labour-days rise, reorganising who works on the farm and when. **Downstream**, the perishable export-oriented citrus market is replaced by organic-certified olive (long-shelf-life, regional Mediterranean markets) and aloe (high-value cosmetics and nutraceutical markets, raw-leaf farm-gate sales today with the option of vertical integration into stabilised aloe gel). Together these changes constitute the traditional-to-adaptive transition that the microsimulation quantifies.

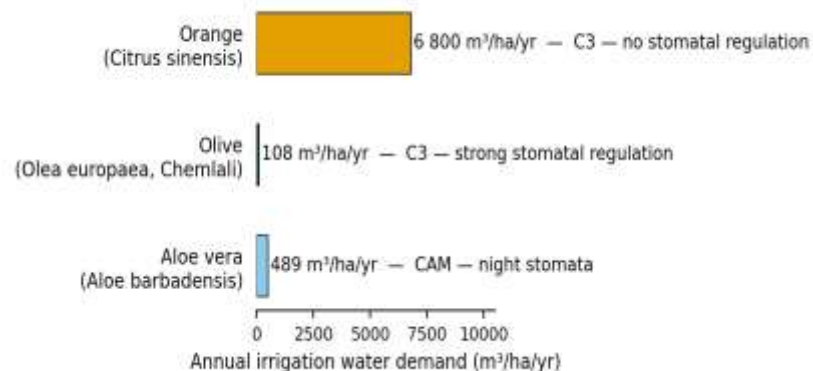


Figure 1. Annual irrigation water demand of the three crops at steady state, with their photosynthetic pathway. The 60-fold differential between citrus and olive demand is physiological, not engineering.

3. CASE-STUDY FARM AND DATA

The case-study farm is a contiguous 7-hectare parcel in Sidi Issa, Takelsa delegation, Nabeul Governorate, Cap Bon. The aquifer is the Mio-Pliocene Cap Bon nappe profonde; soils are sandy-clay topsoil (Calcic Cambisol). The plot was planted in the 1980s with a mixed orange grove (Thomson Navel, Meski and Beldi) at 278 trees per hectare, drip-irrigated from an 86-metre well under a conventional regime (synthetic NPK, chemical herbicide, conventional pesticide). Yields tracked rainfall closely until 2021 (peak 80 t whole-farm in 2018) before collapsing under the 2022–2023 drought; the well failed permanently in 2023. The orchard was uprooted in 2024 and replanted in spring 2025 with 156 olive trees per hectare on eight-by-eight-metre spacing intercropped with aloe vera at 2 400 plants per hectare (densifying to 4 000 from year three). A new 120-metre borehole and 100 m³ storage bassin provide residual summer irrigation.

The replacement system is managed under a deliberate *agroecological regime*, certified organic (ECOCERT). **Weed control** is manual: inter-row desherbage by a seasonal team replaces the herbicide passes of the conventional citrus regime. **Fertilisation** is provided by on-farm compost (20 t/ha/yr) from pruning residues and manure; no synthetic fertiliser. **Pest and disease management** uses biocontrol (pheromone traps, sulphur-based fungicide on olive, none on aloe). **Soil care** combines aloe ground-cover, light mechanical disturbance and compost incorporation, supporting a saturation curve of soil organic carbon from 30 to 35 t C per hectare. **Water harvesting** is integrated via the 100 m³ storage bassin. The labour profile differs materially from the conventional baseline — lower input cost, higher labour input — and the model captures both.

The model draws on three input streams. Plot micro-data (density, geometry, yield, irrigation volumes, labour-days, water bills, sale prices, investment schedule) are taken from the case-study farm records for 2015–2025. Biophysical parameters (yield curves, life-cycle phases, photosynthetic-pathway water demand, Chapman-Richards growth coefficients, soil organic carbon saturation, IPCC Tier-1 carbon coefficients) are taken from the agronomic literature (INRA-Tunis; Sofo et al., 2005; Vicente-Vicente et al., 2016; IPCC, 2019). Climate variables are observed at INM Tunisia station level 2015–2025 and projected 2026–2054 under SSP2-4.5, downscaled with WorldClim v2.1 / CMIP6.

4. METHODOLOGY

The model is a deterministic year-by-year accounting system structured as a six-stage pipeline. **Stage 1** (input layer) combines the three streams above. **Stage 2** (pre-processing) derives whole-farm irrigation demand at the 7-hectare scale, the life-cycle phase of each crop, and the switch point (2024 land

preparation, 2025 planting). **Stage 3** (economic modelling) computes revenue (yield × farm-gate price), operating cost (water, labour, inputs, land rental), the 2024–2027 CAPEX schedule, net cash flow and cumulative cash flow. The labour line captures the agroecological regime: manual desherbage adds seasonal labour-days, partly offset by elimination of herbicide passes; the net labour cost of the agroecological case is approximately 35 percent higher than the conventional alternative tested in Section 5.5. **Stage 4** (water accounting) tracks demand against well/borehole capacity. **Stage 5** (carbon simulation) implements a four-pool balance: olive aboveground biomass on a Chapman-Richards curve (asymptote 8 t C/ha, growth rate 0.08/yr, shape 2) with age-dependent root-shoot ratio; harvested-wood-products and litter pools with IPCC default decay rates; aloe biomass; soil organic carbon on a saturation curve from 30 to 35 t C/ha at rate 0.05/yr. One-off 2025 transition emissions capture loss of mature orange biomass net of casuarina firewood and tillage-induced SOC release. **Stage 6** (scenario analysis) compares three scenarios: orange counterfactual, olive–aloe conventional, and olive–aloe agroecological + organic (baseline). All monetary figures in euros; original modelling in TND at 3.4 TND ≈ €1. Table 1 summarises the key parameters.

Table 1. Key parameters of the microsimulation. All steady-state values; sources in section 3.

Parameter	Orange (A)	Olive (B)	Aloe (B)	Unit
Photosynthetic pathway	C3 (no reg.)	C3 (regulated)	CAM	—
Plantation density	278	156	2 400 → 4 000	plants/ha
Steady-state yield	7.14	7.5	7.2	t/ha/yr
Annual water demand	6 800	108	489.6	m ³ /ha/yr
Whole-farm water demand	47 600	756	3 427	m ³ /yr
Farm-gate price (raw, organic)	320	735	1 320	€/t
Total CAPEX 2024–2027	—	121	121	k€ (combined)
Carbon stock asymptote	—	8.0	0.3	t C/ha
Life expectancy	40	50–100	10	years

5. RESULTS

5.1 Water demand collapses

Figure 2 plots whole-farm annual water demand against effective well/borehole capacity. Under the orange monoculture, demand was 47 600 m³ per year, above the declining capacity of the old well from 2022 and infeasible from 2023. The transition reduces steady-state demand to 4 183 m³ per year (a 91.2 percent reduction), while the new borehole and storage bassin provide approximately 19 200 m³ per year — more than four times the steady-state requirement. The reduction is a physiological consequence of moving from a C3-no-regulation crop to a value chain built around C3-regulated and CAM species; the irrigation technology (drip in both cases) is unchanged.

5.2 Production recovers within four years

Water collapse without production recovery would be a one-sided story. Figure 3 plots whole-farm annual production. Aloe production starts in 2027 at 30 t (year three, partial density) and reaches a steady-state 50 t/yr from 2028; olive production starts in 2028 at 7 t (year four, first commercial fruits) and reaches 52 t/yr from 2031. Combined new-system tonnage matches the historical orange peak by 2028 and exceeds it from 2029 — a result the binding water constraint had made unattainable for the orange counterfactual.

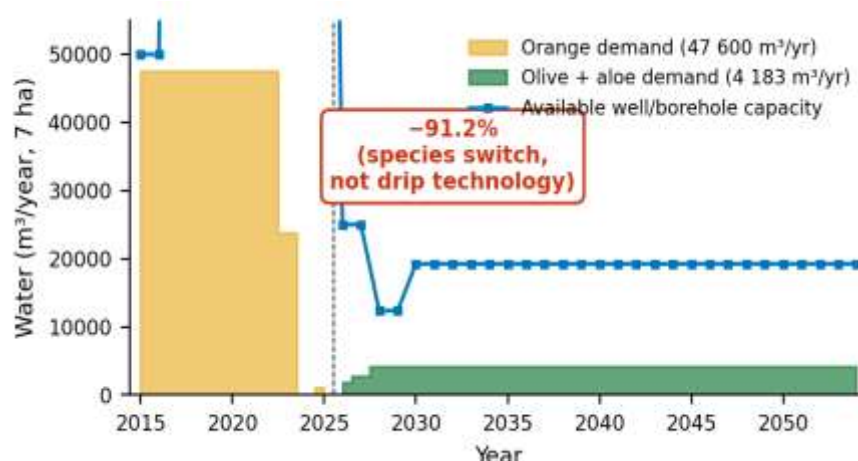


Figure 2. Whole-farm annual water demand and effective borehole capacity, 2015 to 2054. The transition in 2025 reduces demand by 91.2 percent.

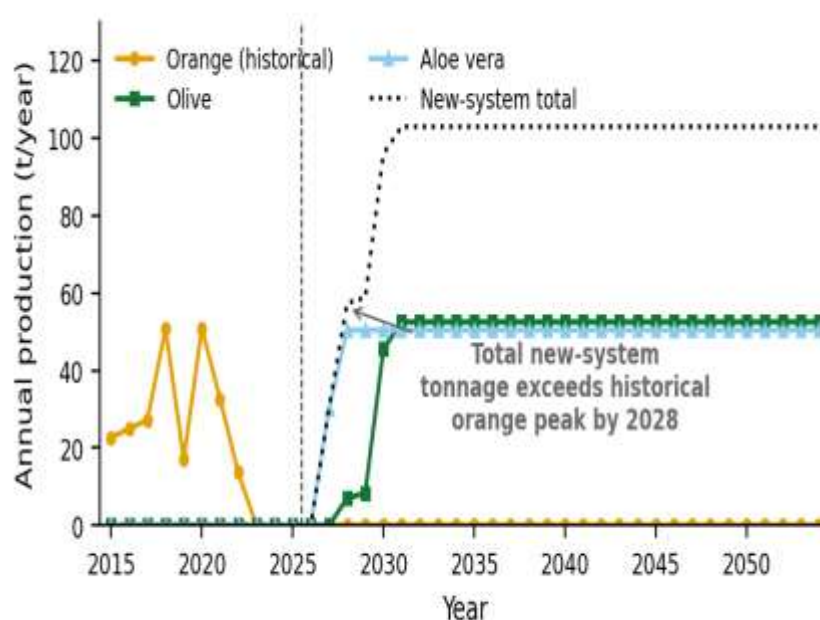


Figure 3. Annual production trajectory of the three crops, 2015 to 2054. New-system tonnage matches historical orange peak by 2028.

5.3 Water and profit decouple: 72-fold reduction in water intensity

The headline result is in Figure 4: water intensity of farm revenue (m^3 irrigation water per 1 000 € of farm-gate revenue) collapses by a factor of 72 across the transition. Under the orange value chain, water intensity ranged from approximately 2 900 m^3 per 1 000 € in peak years (2018, 2020) to 10 800 m^3 per 1 000 € in drought-stricken 2022 — the ratio explodes as yield falls but irrigation demand does not. Under the new value chain from 2031 onward, water intensity stabilises at approximately 41 m^3 per 1 000 € across the 23-year projection horizon. This is the water-profit decoupling result: the farm's revenue stream becomes 72 times less exposed to the binding regional constraint.

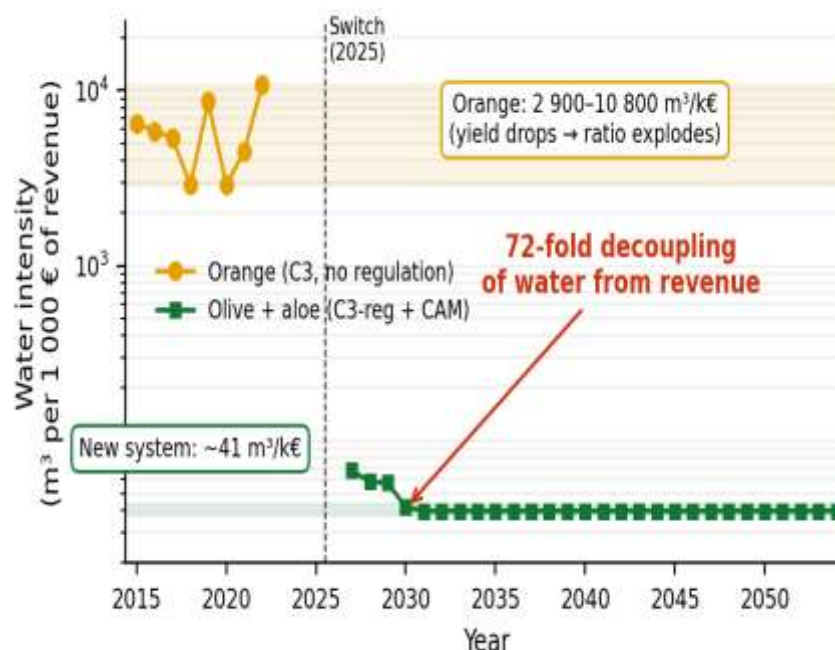


Figure 4. Water intensity of farm revenue, 2015 to 2054 (log scale). Orange band 2 900–10 800 m³ per 1 000 €; new value chain ~41 m³ per 1 000 €.

5.4 Three paybacks converge

Three convergent paybacks operate at three time scales (Figure 5). The **water payback** is immediate at the planting year. The **carbon payback** occurs in year five (2030): one-off transition emissions of approximately 77 t CO₂e in 2025 (mature orange biomass loss net of firewood; tillage-induced 10 percent loss of topsoil SOC) are offset by accumulating olive biomass on its Chapman-Richards curve, the harvested-wood-products pool, and SOC climbing toward 35 t C/ha; the cumulative balance reaches +187 t CO₂e by 2054. The **economic payback** occurs in year nine (2034): cumulative cash flow crosses zero at approximately +€256 thousand, growing thereafter at approximately +€65 thousand per year against the orange counterfactual. These figures reflect *raw aloe leaf sales* (current practice on the case-study farm) and exclude downstream processing of leaves into aloe gel; they are a conservative lower bound.

Table 2. Decomposition of the one-off 2025 transition carbon flux (7-hectare farm, t CO₂e). Negative signs denote emissions, positive signs denote offsets credited in the same accounting year.

Component	t CO ₂ e
Mature orange biomass loss (102 t C × 3.67, 1 946 trees uprooted)	-374
Casuarina windbreak removal (250 trees, sold as firewood)	-115
Tillage-induced topsoil SOC release (10 % of 30 t C/ha over 7 ha × 3.67)	-55
Gross transition emissions	-544
(+) Firewood substitution for fossil heating fuel (≈25 % displacement)	+110
(+) Root and stump biomass retained in soil (≈50 % of belowground over 10 yr)	+92
(+) Pruning residue and woodchip mulch retained on plot	+265
Net 2025 transition flux	-77

The $-77 \text{ t CO}_2\text{e}$ net flux is offset by accumulating olive biomass (Chapman-Richards curve, asymptote 8 t C/ha), the harvested-wood-products pool, and soil organic carbon climbing along its saturation curve from 30 toward 35 t C/ha at $0.05/\text{yr}$; the cumulative balance crosses zero in 2030 and reaches $+187 \text{ t CO}_2\text{e}$ by 2054.

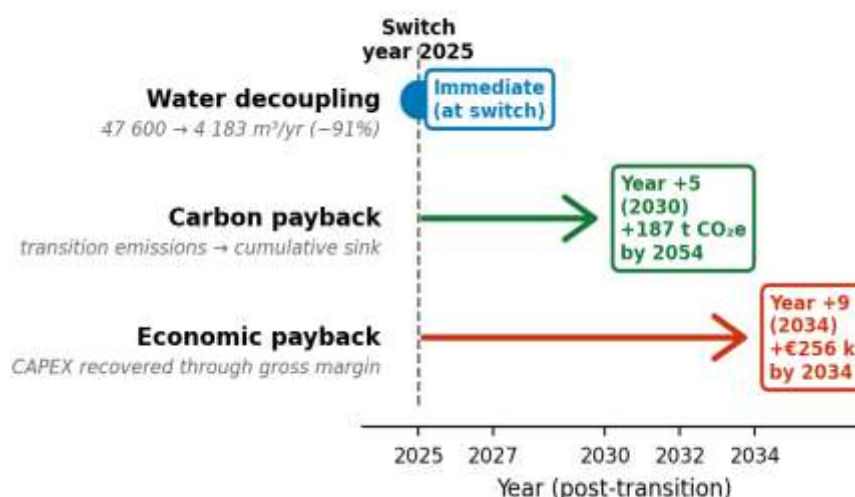


Figure 5. Three convergent paybacks of the traditional-to-adaptive transition: water immediate (2025), carbon year +5 (2030), economic year +9 (2034).

5.5 Robustness: isolating the value-chain transition from the agroecological regime

The transition combines two changes: a value-chain transition (replacing citrus with olive plus aloe and reconfiguring upstream and downstream nodes) and an agroecological management regime layered on top (manual desherbage, on-farm compost, biocontrol, no synthetic fertiliser, certified organic). Figure 6 isolates the two effects. The orange counterfactual (no transition, tanker-water imports) accumulates a deficit of approximately €388 thousand over 2024–2034. The value-chain transition under *conventional* inputs and prices — synthetic fertiliser, chemical herbicide, conventional pesticide, no organic premium — yields approximately +€4 thousand: the value-chain transition alone, even without agroecology, closes the €388 thousand gap. The full agroecological regime with organic certification yields approximately +€247 thousand, a further €244 thousand uplift.

The conventional comparator holds yield identical to the agroecological case. In practice, conventional management with synthetic NPK and chemical pesticide may sustain a 10–20 percent higher short-run yield at the cost of soil organic carbon, biodiversity and human-health exposures not priced in the model. Running the conventional comparator at a +15 percent yield raises its 2024–2034 cumulative cash flow to approximately +€48 thousand — still about €199 thousand below the agroecological + organic case, and still leaving the value-chain transition as the dominant lever for the physical decoupling result. The qualitative ranking of the three scenarios is therefore robust to the yield-parity assumption; the magnitude of the agroecological premium narrows, but the agroecological case does not lose its rank. The value-chain transition is the decisive lever for the physical decoupling result of Section 5.3. The agroecological regime layered on top adds substantial economic margin under the price premium, and — independently of that margin — underwrites the environmental outcomes (soil organic carbon recovery to 35 t C/ha , biocontrol-based pest management, elimination of synthetic-pesticide exposure for the farm team) that are not monetised in the present model but will be quantified in the multi-criteria scoring layer described in Section 7.1.

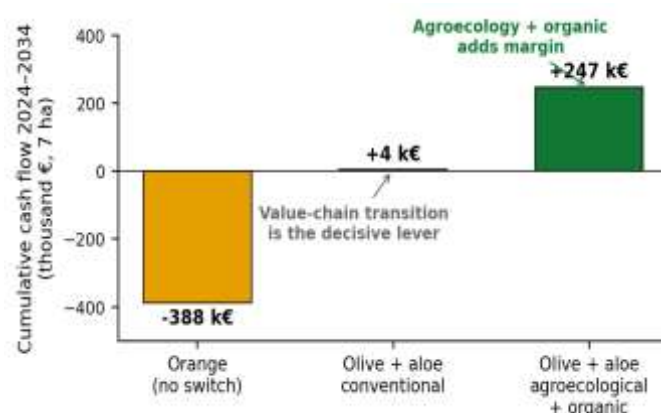


Figure 6. Cumulative cash flow 2024–2034 under three scenarios (in €). The value-chain transition alone closes the gap; agroecology with organic certification adds a further €244 thousand.

6. DISCUSSION

6.1 A complementary lever within the irrigation-adaptation toolkit

The principal contribution is methodological: a transparent, single-farm microsimulation tracking water, profit and carbon jointly over thirty years through a documented traditional-to-adaptive transition, demonstrating that the three outcome streams can be decoupled from irrigation water by reconfiguring the production value chain on which the irrigation system is built. The substantive implication is not that irrigation engineering becomes irrelevant — it remains the necessary lever wherever water supply meets crop demand within the engineering envelope. The implication is that the toolkit needs a second lever for the regime documented here, where supply has fallen below the absolute demand of the established crop. Improving drip uniformity from 85 to 90 percent on a citrus orchard demanding 6 800 m³/ha/yr can recover application losses, but it cannot bridge a 6 800-to-zero gap. A value-chain transition to a system whose dominant crop demands 108 m³/ha/yr operates on a different physical magnitude and addresses a different binding constraint. The two levers are complementary rather than substitutes: irrigation engineering optimises *how* water is applied to the crop; value-chain transition reconfigures *which crop* the irrigation system is designed to serve. Both belong in the Mediterranean adaptation toolkit; the climate signal in Cap Bon has pushed parts of the region into the regime where the second lever is now the binding one.

6.2 Replicability conditions across Mediterranean perennial systems

The decoupling result is conditional on three structural features. First, the alternative value chain must be feasible: regional climate, soil and market conditions permit olive and aloe as viable replacements for citrus. Second, the operator must absorb the front-loaded CAPEX (approximately €121 thousand on a 7-hectare farm) and the loss-making establishment phase. Third, the operator must access the agroecological management capability and certification regime supporting the long-run margin. The first holds across much of the Mediterranean citrus belt; the second is the principal binding constraint for smallholders and the natural locus for blended-finance instruments; the third is not strictly required, as Section 5.5 demonstrates.

6.3 Model boundaries

Five boundaries are worth stating. (i) Yield is deterministic on the age curve; alternance in olive (±30–50 percent biennial) is not modelled. (ii) The climate driver is the deterministic SSP2-4.5 trajectory; a stochastic-rainfall layer is not yet integrated. (iii) Carbon accounting excludes embodied emissions from compost transport, on-site processing energy, and aloe-gel manufacturing. (iv) **Economic figures**

assume sale of raw aloe leaves only, reflecting current commercial practice; downstream processing into stabilised aloe gel is excluded and represents the most consequential conservative assumption. (v) The microsimulation is single-farm; scaling would borrow from the AFFOR architecture (Ryan et al., 2025).

7. NEXT STEPS AND EXTENSIONS OF THE SIMULATION MODEL

The microsimulation developed here is the first iteration of a deliberately modular framework. Five extensions are already identified and will be incorporated in subsequent versions of the model.

7.1 Quantifying the benefits of the traditional-to-organic transition explicitly

The present model treats organic certification as a price-premium effect, but the agroecological transition produces additional benefits not yet monetised: soil microbial-biomass recovery and biodiversity indicators (earthworm density, pollinator visits, beneficial insects), human-health outcomes for the farm team from eliminated exposure to synthetic pesticides and herbicides, and consumer-side health attributes of organic produce. A subsequent version will integrate these dimensions through a multi-criteria scoring layer, allowing the agroecological dividend to be quantified beyond the price premium.

7.2 Modelling the downstream value-chain step from raw leaf to processed aloe gel

The aloe value chain offers substantial scope for vertical integration: stabilised aloe gel commands farm-gate-equivalent prices an order of magnitude above raw leaf, and small-scale solar-powered processing units are technically and economically feasible at the 7-hectare scale. A subsequent version will model the CAPEX, processing-energy, packaging and quality-control parameters of on-farm aloe-gel production, quantifying both the additional value capture and the embodied emissions of the processing step.

7.3 Alternative crop combinations and scenario variants

The olive–aloe pairing modelled here is one of several feasible agroecological combinations for the Mediterranean perennial belt. A scenario library will systematically test alternatives — olive with quinoa, almond with prickly pear, fig with aromatic and medicinal plants, olive with aloe arborescens versus barbadensis — characterising the response surface of the decoupling result across the feasible-combination space.

7.4 Stochastic climate and policy layers

The deterministic SSP2-4.5 trajectory does not capture inter-annual variability or cash-flow risk. A subsequent version will add a stochastic-rainfall layer calibrated to 2015–2025 variability, propagated through a crop-water-response function to generate distributions of net cash flow, water-deficit-days and carbon flux. A parallel policy layer will introduce a binding water-rationing constraint tied to regional dam fill rates, together with EU ETS and voluntary-carbon-market price scenarios.

7.5 Scaling from a single farm to a regional microsimulation

The present framework is single-farm by design. The natural next step is to scale to a representative sample of Cap Bon smallholdings with heterogeneous starting conditions, soil codes, water rights, operator age and risk profiles, borrowing directly from the AFFOR architecture (Ryan, Kilcline and O'Donoghue, 2025). A regional microsimulation would generate distributions of transition viability across the farm population and identify the segments where the value-chain transition delivers the largest decoupling dividend — informing the design of blended-finance instruments and the targeting of agroecological extension services.

8. CONCLUSION

This paper has developed a single-farm biosystem microsimulation and applied it to a documented traditional-to-adaptive transition on a 7-hectare farm in Cap Bon, Tunisia. The headline result is the **decoupling of water from profit**: replacing the traditional citrus value chain with an olive–aloe value chain reduces water intensity per unit of farm revenue by a factor of 72 (from 2 900–10 800 to approximately 41 m³ per 1 000 €). Three convergent paybacks support this: water decoupling is immediate, carbon payback occurs in year five (+187 t CO₂e by 2054), and economic payback in year nine (+€256 thousand cumulative over the no-transition counterfactual). Both monetary and environmental profitability are achieved together. The value-chain transition alone closes the €388 thousand gap against the no-transition counterfactual; the agroecological regime layered on top adds approximately €244 thousand of margin and underwrites the environmental outcomes. The methodological contribution is a transparent, parameter-traceable architecture linking water, carbon and profit through a documented value-chain transition, applicable to other Mediterranean perennial systems where absolute water demand has become the binding regional constraint.

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