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Accelerating Agriculture 4.0 without Accelerating Depletion: A Policy Framework for a Sustainable Digital Agrifood System in Morocco.

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Abstract

Agriculture 4.0, the combined use of sensors, remote sensing, artificial intelligence, big data and robotics in farming, is increasingly presented as the route by which water-scarce countries can raise productivity, adapt to climate change and secure their food supply. The policy literature that accompanies this promise is largely organised around adoption: it identifies the barriers that keep farmers from taking up digital tools and recommends instruments to lower them. This article argues that, for Morocco, an adoption-centred agenda is necessary but insufficient, and in one respect counter-productive. Drawing on technology adoption theory, on the rebound effect and on the theory of common-pool resources, and on Morocco's experience with subsidised drip irrigation and solar pumping, it builds a theoretical research model based on three propositions. First, a technology that lowers the private cost of using a scarce resource can raise aggregate use of that resource unless use is capped, so that subsidising digital efficiency without a cap can accelerate groundwater depletion. Second, the largest public return to Agriculture 4.0 in the irrigated sector is expected to come from making groundwater abstraction observable, a necessary but not sufficient condition for enforceable allocation. Third, in the rainfed cereal sector, where output and import needs depend primarily on rainfall, the value of digital tools lies in harvest forecasting and risk transfer. FAOSTAT data illustrate the problem: since 1966, the olive area alone has expanded by the equivalent of about 89 per cent of the increase in the area equipped for irrigation. The resulting framework makes the conventional policy levers conditional, sequenced and differentiated between irrigated and rainfed systems, and proposes indicators and tests for each proposition.

Keywords: Agriculture 4.0; Digital agriculture; Technology adoption; Rebound effect; Groundwater governance; Food security; Morocco.

Résumé

L'Agriculture 4.0, c'est-à-dire l'usage combiné de capteurs, de la télédétection, de l'intelligence artificielle, des données massives et de la robotique dans l'agriculture, est de plus en plus présentée comme la voie par laquelle les pays en situation de stress hydrique peuvent accroître leur productivité, s'adapter au changement climatique et sécuriser leur approvisionnement alimentaire. La littérature de politique publique qui accompagne cette promesse est largement centrée sur l'adoption : elle identifie les obstacles qui freinent l'adoption des outils numériques par les agriculteurs et recommande des instruments pour les lever. Cet article soutient que, pour le Maroc, une stratégie centrée sur l'adoption est nécessaire mais insuffisante, et sur un point contre-productive. En s'appuyant sur la théorie de l'adoption technologique, sur l'effet rebond et sur la théorie des ressources communes, ainsi que sur l'expérience marocaine de l'irrigation localisée subventionnée et du pompage solaire, il construit un modèle de recherche théorique fondé sur trois propositions. Premièrement, une technologie qui réduit le coût privé d'utilisation d'une ressource rare peut en accroître l'usage total si cet usage n'est pas plafonné ; subventionner l'efficience numérique sans plafond peut donc accélérer l'épuisement des nappes. Deuxièmement, dans le secteur irrigué, le principal rendement public de l'Agriculture 4.0 devrait provenir de l'observation des prélèvements d'eau souterraine, condition nécessaire mais non suffisante d'une allocation applicable. Troisièmement, dans le secteur céréalier pluvial, où la production et les besoins d'importation dépendent d'abord de la pluie, la valeur des outils numériques réside dans la prévision des récoltes et le transfert des risques. Les données de FAOSTAT illustrent le problème : depuis 1966, la seule superficie en olivier a progressé de l'équivalent d'environ 89 % de la hausse de la superficie équipée pour l'irrigation. Le cadre qui en résulte rend les leviers de politique publique conditionnels, séquencés et différenciés entre systèmes irrigué et pluvial, et propose des indicateurs et des tests pour chaque proposition.

Mots-clés : Agriculture 4.0 ; Agriculture numérique ; Adoption technologique ; Effet rebond ; Gouvernance des eaux souterraines ; Sécurité alimentaire ; Maroc.

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1. INTRODUCTION

Agricultural systems in North Africa face a set of pressures that are individually familiar and jointly unprecedented. Rainfall is becoming more variable, aquifers are being drawn down faster than they recharge, food demand keeps rising, and dependence on imported staples exposes households and public budgets to world-market shocks. A common prescription has emerged: the digital transformation of agriculture, or Agriculture 4.0 (Rose & Chilvers, 2018; Schroeder et al., 2021; Trendov et al., 2019), which promises to reconcile higher productivity with lower resource use (Basso & Antle, 2020; Walter et al., 2017).

The policy literature built around this promise catalogues the barriers that separate availability from use and concludes that public policy must lower them through subsidies and credit, infrastructure, training and data regulation (Birner et al., 2021; Deichmann et al., 2016; Klerkx et al., 2019; Parra-López & Carmona-Torres, 2026). The implicit causal chain runs from policy to adoption, from adoption to efficiency, and from efficiency to sustainability and food security. This article accepts the first half of that chain and questions the second. When a technology lowers the water needed per hectare, it also raises the profitability of irrigated production, and farmers can respond by irrigating more land or switching to more water-intensive crops; at basin scale, the water "saved" is then frequently redeployed rather than conserved (Grafton et al., 2018; Pérez-Blanco et al., 2020; Pfeiffer & Lin, 2014; Ward & Pulido-Velázquez, 2008). Morocco offers one of the clearest illustrations: subsidised conversion to drip irrigation coincided with an expansion of irrigated area and continued groundwater depletion (Jobbins et al., 2015; Le Page et al., 2025; Molle & Tanouti, 2017; Ouassissou et al., 2022), while solar pumping, by turning the marginal cost of lifting water into a sunk capital cost, has removed the price signal that once rationed abstraction (Closas & Rap, 2017; Laator & El Alaoui, 2026b).

The subject of this research is the design of public policy for Agriculture 4.0 in a water-scarce country, Morocco. Its objective is to develop a policy framework that accelerates the adoption of digital agricultural technologies without accelerating the depletion of water resources, by answering the following research question: under which policy conditions do digital efficiency gains translate into resource savings rather than into greater resource use? The analysis rests on three theories, the economics of technology adoption, the rebound effect applied to irrigation

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efficiency and the theory of common-pool resources, which together yield a theoretical research model built on three propositions.

The article makes three contributions. It reframes the barriers to adoption in terms of the market failures that would justify intervention; it makes explicit the conditions under which a digital efficiency gain translates into lower resource use, and argues that Agriculture 4.0 is itself the technology that can make water caps enforceable; and it distinguishes the roles of digital tools in Morocco's irrigated and rainfed systems, from which it derives a sequenced policy framework and a set of outcome indicators for its evaluation. The novelty lies in the combination rather than in any single element. The irrigation-efficiency literature establishes the rebound but is mainly concerned with conventional irrigation technologies (Grafton et al., 2018; Pérez-Blanco et al., 2020); the policy literature on digital agriculture is organised around adoption (Birner et al., 2021; Parra-López & Carmona-Torres, 2026); and the groundwater-governance literature emphasises enforcement and its political economy (Molle & Closas, 2020). The article connects the three and adds a sectoral typology, a sequencing rule and three testable propositions, illustrated with descriptive FAOSTAT evidence.

The research is structured as follows. Section 2 presents the theoretical, methodological and empirical framework. Section 3 describes Morocco's dual agrifood system. Sections 4 to 6 develop, in turn, the reinterpretation of adoption barriers, the efficiency trap and the role of Agriculture 4.0 as a governance technology. Section 7 turns to the rainfed sector, Section 8 presents the theoretical research model and the integrated policy framework, Section 9 discusses sequencing, risks and evaluation, and Section 10 concludes.

2. THEORETICAL, METHODOLOGICAL AND EMPIRICAL FRAMEWORK

2.1. Agriculture 4.0 as a set of economic functions

Definitions of Agriculture 4.0 usually proceed by enumeration: the Internet of Things, artificial intelligence, big data, remote sensing, robotics and blockchain (Klerkx & Rose, 2020; Rose & Chilvers, 2018). For policy design, what matters is rather the economic function a technology performs, because the function determines who benefits, which market failures are involved and which side-effects are likely. Table N°1 distinguishes four functions. Most of what is new in Agriculture 4.0 is informational: sensors, satellites and models change what is known, by whom and at what cost, and the value of information depends on the decision it informs. Function (1) is

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where the productivity-sustainability promise is usually located, but also where the rebound mechanism operates. Function (3), often discussed mainly in connection with traceability, lowers the cost to a public authority of observing what farmers do with common-pool resources. Because the data generated by one function feed the others, the question of who controls the data determines who captures the value (Birner et al., 2021; Wolfert et al., 2017).

Table N°1 : Agriculture 4.0 technologies classified by economic function

Function	Typical technologies	Primary user	Main policy issue
(1) Reducing input per unit of output	Soil-moisture sensors, IoT-controlled drip, variable-rate application	Farmer	Rebound: lower unit cost raises total resource use
(2) Reducing information cost for decisions	Mobile advisory, AI disease detection, weather and price services	Farmer, adviser	Quality of advice; learning externalities
(3) Reducing monitoring and verification cost	Satellite monitoring, smart water meters, evapotranspiration mapping, traceability	State, buyer, insurer	Data governance; enforcement; trust
(4) Substituting capital for labour	Robotics, autonomous machinery	Large farms	Rural employment; farm-size bias

Source: Authors. A single device may perform several functions: a networked soil-moisture sensor reduces water per hectare (1), informs the schedule (2) and, if its data are shared, makes use observable (3).

2.2. Theoretical foundations

The framework rests on three bodies of theory. The economics of technology adoption shows that non-adoption is often rational, because returns are heterogeneous across farms (Feder et al., 1985; Foster & Rosenzweig, 2010; Suri, 2011). The rebound effect, applied to irrigation efficiency, shows that a gain in application efficiency reduces aggregate water use only under specific conditions, because it raises the return to irrigating and reduces return flows (Grafton et al., 2018; Pérez-Blanco

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et al., 2020). And the theory of common-pool resources identifies monitoring as one of the conditions under which such resources can be governed at all (Ostrom, 1990).

Each proposition of the research model is derived from one of these bodies of theory and from the empirical studies that support it. Proposition 1 derives from the rebound literature on irrigation efficiency (Grafton et al., 2018; Pérez-Blanco et al., 2020; Pfeiffer & Lin, 2014; Ward & Pulido-Velázquez, 2008) and from Moroccan evidence on drip irrigation and solar pumping (Laator & El Alaoui, 2026b; Molle & Tanouti, 2017). Proposition 2 derives from the theory of common-pool resources (Ostrom, 1990) and from the literature on groundwater governance (Closas & Villholth, 2016; Molle & Closas, 2020). Proposition 3 derives from the literature on digital advisory services and index insurance (Carter et al., 2017; Fabregas et al., 2019) and from evidence on the rainfall sensitivity of Moroccan cereal yields and agricultural trade (Laator, 2026; Laator & El Alaoui, 2026a). The variables associated with each proposition, namely irrigated area, consumptive use and piezometric levels for the first, metered volumes and enforcement for the second, and forecast accuracy, import timing and price volatility for the third, are drawn from these studies and from the water-accounting literature (Karimi & Bastiaanssen, 2015); they are listed in Table N°4.

2.3. Method and empirical basis

The research adopts a post-positivist epistemological position: the mechanisms it studies, namely adoption decisions, the rebound effect and the governance of common-pool resources, are assumed to exist independently of the observer but to be knowable only imperfectly and provisionally. Its mode of reasoning is hypothetico-deductive: propositions are deduced from established theories, confronted with existing evidence, and translated into indicators and tests for later empirical validation. A conceptual approach was chosen because the farm- and aquifer-level data needed to estimate the effects of digital technologies on water use in Morocco are not yet available, and because the aim is to build a framework that can guide such estimation rather than to carry it out.

In practice, this conceptual and analytical approach combines three elements: two simple accounting identities, which make the rebound mechanism explicit; a descriptive analysis of FAOSTAT land-use series; and a structured synthesis of peer-reviewed evidence on digital agriculture, irrigation efficiency and groundwater governance, read together with Moroccan policy documents and legal texts. The literature was selected purposively rather than through a systematic review. It covers three bodies of work: reviews and empirical studies of the adoption of digital and

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precision agriculture; theoretical and empirical studies of the irrigation efficiency paradox and of groundwater governance; and case studies of Moroccan irrigation, groundwater and cereal production, with priority given to peer-reviewed work published since 2015. Every reference was checked against bibliographic databases and, wherever an abstract or official text was available, the claim attributed to each source was compared with it. The Moroccan evidence draws in addition on the authors' published work on climate, cereal yields, food availability and agricultural trade (Laator, 2026; Laator & El Alaoui, 2026a; Laator et al., 2026) and on solar pumping (Laator & El Alaoui, 2026b).

3. MOROCCO'S DUAL AGRIFOOD SYSTEM

Morocco runs two agricultural systems side by side. The irrigated sector, made up of large public schemes and of private groundwater-based irrigation in plains such as the Souss, the Saïss, Tadla and Berrechid, concentrates high-value production and most agricultural exports; its binding constraint is water. The rainfed sector covers the large majority of cultivated land and produces most of the country's cereals. Cereal yields respond to seasonal rainfall (Laator, 2026), as does milk production in the long run, through water and fodder availability (Laator et al., 2026), and the agricultural trade balance responds strongly and persistently to climatic conditions: in dry years, imports rise to fill the gap between domestic demand and a shrinking harvest (Laator & El Alaoui, 2026a). For this sector, the relevant constraint is less water availability in the long run than rainfall risk in the short run.

Public policy has long treated the two sectors asymmetrically. Alongside the Green Morocco Plan (2008–2020), the National Programme for Irrigation Water Saving subsidised the conversion of surface irrigation to drip through the Agricultural Development Fund. The subsidy remains in force: under the joint order currently governing it, the state covers 100 per cent of the cost of individual drip projects for small farmers, 75 per cent for holdings of 5 to 20 hectares and 60 per cent above 20 hectares, within per-hectare ceilings (Kingdom of Morocco, 2022). Revealingly, the eligible components include not only emitters and pipes but also wells, boreholes, pumping equipment and storage basins, that is, the means of abstraction itself. Field research in the Berrechid plain shows that state subsidies encourage water-intensive and energy-inefficient groundwater-based systems that increase pressure on aquifers (Ouassissou et al., 2022). The successor strategy, Generation Green 2020–2030, makes digitalisation a cross-cutting initiative, with the target of

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connecting two million farmers and other users to agricultural e-services by 2030 (Ministry of Agriculture, Maritime Fisheries, Rural Development and Water and Forests, 2020), while Law 36-15 on water provides the legal basis for authorisations, metering and participatory aquifer management (Kingdom of Morocco, 2016). Enforcement on the ground, particularly for groundwater, has remained limited (Closas & Villholth, 2016; Molle & Closas, 2020).

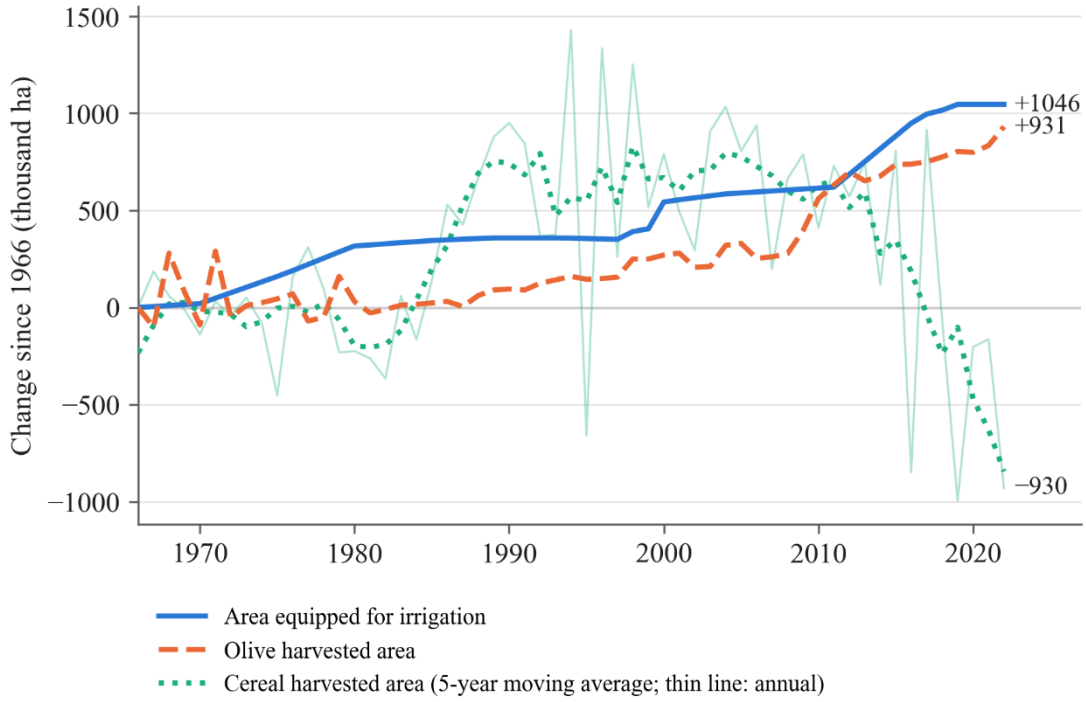
The national strategy Digital Morocco 2030 sets the connectivity objectives on which rural digitalisation depends (Ministry of Digital Transition and Administrative Reform, 2024). The state thus promotes, at the same time, the digitalisation of farm services and the subsidised equipment of wells and pumps, without an explicit link between the two.

The outcome is sobering on one point. Drip conversion has raised water productivity at field level, but it has been accompanied by an expansion of irrigated area and a shift towards water-intensive crops, while groundwater tables have kept falling (Aglagal et al., 2025; Jobbins et al., 2015; Molle & Tanouti, 2017), with declines of 20 to 65 metres documented over three decades (Hssaisoune et al., 2020). Remote sensing documents the proliferation of small storage basins in phase with aquifer depletion (Le Page et al., 2025), and adopters of solar pumping in the Tadla plain abstract more groundwater than non-adopters (Laator & El Alaoui, 2026b).

Figure N°1 shows where the equipped hectares went. The FAOSTAT series are expressed in thousand hectares and as changes relative to 1966; because comparisons between single years are sensitive to the choice of base and end years, and cereal areas fluctuate strongly with rainfall, cereal areas are also summarised as multi-year averages. Between 1966 and 2022, the area equipped for irrigation increased by about 1,046 thousand hectares and the olive harvested area alone by about 931 thousand hectares, the equivalent of 89 per cent of that increase; 70 per cent of the olive expansion occurred after 2008, coinciding with the Green Morocco Plan. This ratio compares two aggregate increases; it is not an attribution of newly equipped land, and it is sensitive to the period: across start years from 1961 to 1970 and end years from 2020 to 2024 it ranges from 50 to 101 per cent (median 87 per cent; the lowest values arise with 1968, a year of unusually high recorded olive area), and it is 77 per cent with five-year averages. From the late 1970s onwards, the olive expansion exceeds the increase in equipped area, a reminder that much of it is rainfed. Being descriptive, the comparison identifies no causal effect of irrigation policy on crop choices. The cereal harvested area rose until the 2000s, to about 5.3 million hectares on average in 1991–2010,

and has since fallen to about 3.8 million hectares in 2020–2024, partly under a run of drought years: a decline of about 610 thousand hectares between the averages of 1964–1968 and 2020–2024. Taken together, these trends are difficult to reconcile with the view that irrigation has primarily served to stabilise cereal output.

Figure N°1 : Change since 1966 in the area equipped for irrigation and in the olive and cereal harvested areas, Morocco, 1966–2022 (thousand hectares)



Source: Authors' calculations from FAOSTAT (Crops and livestock products, area harvested: Olives and Cereals, primary; Land use: land area equipped for irrigation). End-point labels give the 1966–2022 change; for cereals, the thin line is annual and the dotted line a centred 5-year moving average. The figure is descriptive and does not identify causal effects.

The evidence is not uniform: a regional study finds a structural increase in cereal production after 2008 in the three main north-western producing regions, which it attributes to irrigation and improved inputs (Ed-dahmany et al., 2025). Drip irrigation was the “smart” technology of the 2000s; the question is whether the digital technologies of the 2020s will repeat its trajectory.

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4. BARRIERS TO ADOPTION, RECONSIDERED

The literature identifies four families of barriers to the adoption of Agriculture 4.0: the digital divide, cost, skills and data governance (Deichmann et al., 2016; Mehrabi et al., 2021; Žáková Kroupová et al., 2026). The digital divide is strongly size-biased: only 24–37 per cent of farms under one hectare are covered by 3G or 4G networks, against 74–80 per cent of farms over 200 hectares (Mehrabi et al., 2021). Adoption is also uneven across technologies: satellite guidance has spread as fast as any agricultural technology in history, whereas variable-rate application rarely exceeds 20 per cent of farms, and precision agriculture is almost absent from non-mechanised small farms (Lowenberg-DeBoer & Erickson, 2019). Farmers, moreover, have little reason to trust platforms whose use of their data they cannot observe (Jakku et al., 2019; Wiseman et al., 2019).

Listing barriers, however, does not justify public intervention. Suri (2011) shows that apparently puzzling low adoption of hybrid maize in Kenya is well explained by heterogeneous net benefits; the farmers with the highest gross returns did not adopt because poor infrastructure made the technology costly to acquire. Non-adoption can thus signal either low returns, in which case a subsidy wastes public resources, or a genuine barrier, which is then the appropriate target. The relevant question is where private and social returns diverge. Table N°2 maps each barrier onto the market failure that would justify intervention and onto the corresponding instrument.

Table N°2 : From barriers to market failures to instruments

Barrier	Underlying market failure	Justified instrument	Instrument to avoid
High upfront cost	Credit constraints; lumpy investment	Credit guarantees, leasing, shared-service models	Unconditional subsidies on resource-using equipment
Low skills, uncertain returns	Learning externalities	Public extension, demonstration plots	Mass subsidies without advice
Poor connectivity	Public-good and network character of infrastructure	Universal-service obligations, public rural coverage	Farm-level vouchers alone

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Barrier	Underlying market failure	Justified instrument	Instrument to avoid
Data distrust	Asymmetric information; hold-up risk	Data rights, portability, transparency rules	Leaving terms to platforms
Resource externalities	Private user does not bear the social cost	Enforceable caps, metering, pricing	Efficiency subsidies without a cap

Source: Authors.

The adoption literature also cautions against treating adoption as a purely individual decision: perceived relative advantage and motivation are the factors most often associated with adoption (Pathak et al., 2019), and research has neglected interactions between farmers, institutions and technologies (Shang et al., 2021).

The learning externality is probably the strongest justification for public support to digital advisory services. A meta-analysis suggests that digital agricultural information raised yields by about 4 per cent and the odds of adopting recommended inputs by 22 per cent, and that market distortions keep such services below the efficient scale (Fabregas et al., 2019); other evidence is more mixed (Aker et al., 2016; Cole & Fernando, 2021). Because the cost per farmer is low, the case for public co-financing remains strong. In Morocco, the National Office for Agricultural Advice (ONCA) and the OCP group's Al Moutmir programme, launched in 2018, provide channels through which such services can be scaled.

The last row of Table N°2, the resource externality, is not usually listed as a barrier to adoption at all. It is rather a reason why adoption may carry social costs that do not appear in the farmer's calculation, and it is the subject of the next section.

5. THE EFFICIENCY TRAP

The mechanism can be stated with two accounting identities that distinguish the water a farmer applies from the water that is actually consumed. Let A be the irrigated area, c the consumptive use per hectare (crop evapotranspiration) and e the application efficiency, that is, the share of applied water that the crop consumes. Withdrawals W denote the water abstracted from aquifers or diverted from rivers for irrigation; ignoring conveyance losses, they equal the water applied to fields, which is c / e per hectare. Total withdrawals W and total consumptive use C are then:

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$W = A \times c / e$ and $C = A \times c$ (1)

A technology that raises application efficiency e lowers the water applied per hectare for a given crop. But it also lowers the cost of delivering each unit of consumptive use and raises the return to irrigating, so that farmers may expand A, by irrigating land previously left rainfed or adding a season, and raise c, by switching to more water-intensive crops or watering more fully. Taking logarithms and differentiating with respect to e:

$$\frac{d \ln W}{d \ln e} = -1 + \frac{d \ln A}{d \ln e} + \frac{d \ln c}{d \ln e} \quad (2a)$$

$$\frac{d \ln C}{d \ln e} = \frac{d \ln A}{d \ln e} + \frac{d \ln c}{d \ln e} \quad (2b)$$

According to (2a), withdrawals fall as efficiency improves only if the combined response of area and of consumptive use per hectare is smaller than one; beyond that, they rise, the agricultural analogue of the Jevons paradox. According to (2b), consumptive use, which is what depletes a basin, does not fall at all unless area or consumptive use per hectare declines. The difference $W - C$ is the water not consumed by the crop: part returns to aquifers and rivers, part evaporates from soil and canals. Net depletion therefore depends on consumptive use and non-beneficial evaporation, not on withdrawals as such, so a field that applies less water may leave the basin with less water if its consumptive use is unchanged or higher (Grafton et al., 2018; Pérez-Blanco et al., 2020). Reducing non-beneficial evaporation is the one channel of genuine basin-scale saving, and any expansion of area or crop water use eats into it.

The evidence supports the mechanism. In the Upper Rio Grande, Ward and Pulido-Velázquez (2008) find that water conservation subsidies are unlikely to reduce water use; in Kansas, Pfeiffer and Lin (2014) show that a subsidised shift to more efficient systems increased groundwater extraction, partly through more water-intensive crops; and reviewing more than 230 studies, Pérez-Blanco et al. (2020) conclude that efficient irrigation is not, by itself, a water conservation tool (see also Sears et al., 2018). The rebound is not the only possible outcome (Dumont et al., 2013), but in Morocco drip conversion has been associated with higher crop density, more water-intensive crops and the reuse of "saved" water to expand cultivated area (Molle & Tanouti, 2017).

Digital technologies are not exempt. A sensor-driven scheduler applies water only when the crop needs it, which is correct at field level but insufficient at basin level: a technology that raises the output obtained from a cubic metre raises the value of that cubic metre to the farmer. This qualifies a common conclusion of the precision-farming literature, that the environmental benefits of

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precision farming can justify public incentives for adoption (Finger et al., 2019). The argument holds where the resource-using activity cannot expand; where it can, as with groundwater, the same incentive can increase total use. The same logic applies to precision fertilisation, which can raise total nitrogen use if it makes intensive cropping profitable on more land: the sign of the environmental effect is a property of the policy environment rather than of the technology.

Proposition 1 (Conditionality of sustainability gains). *A technology that lowers the private cost of using a scarce resource per unit of output is guaranteed to reduce aggregate use of that resource only if the expansion of the resource-using activity is constrained, or if the resource is priced at its scarcity value. In the absence of either condition, public support for its adoption may increase aggregate resource use.*

The policy implication is that subsidies for resource-saving Agriculture 4.0 technologies should be conditional: granted only where resource use is subject to an enforceable cap, and ideally coupled with a reduction in the individual allocation. Where no cap exists, the priority is to build one. The difficulty is that groundwater caps are notoriously hard to enforce, in part because abstraction by thousands of private wells is costly to observe.

6. AGRICULTURE 4.0 AS A GOVERNANCE TECHNOLOGY

A water authority cannot cap what it cannot measure. Monitoring is one of the conditions that distinguish commons that endure from commons that collapse (Ostrom, 1990). It is not, however, the only one: reviewing state-centred groundwater governance across countries, Molle and Closas (2020) find its performance to have been dismal and argue that, beyond shortages of data and staff, weak enforcement is rooted in the political economy of groundwater use. Better information is therefore a necessary condition for enforceable allocation, not a sufficient one.

Function (3) of Table N°1 changes the cost structure of monitoring. Satellite-based evapotranspiration maps estimate actual consumptive use independently of farmers' declarations; seasonally accumulated maps can be used with confidence in water accounting (Karimi & Bastiaanssen, 2015), and FAO's open WaPOR database, evaluated across Africa, is judged of sufficient quality for monitoring water management, although it overestimates evapotranspiration in irrigated areas (Blatchford et al., 2020); such products support allocation at aquifer scale, not sanctions against an individual farmer. High-resolution imagery identifies irrigated plots and storage basins (Le Page et al., 2025), and networked meters can be tied to individual authorisations.

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The most valuable user of Agriculture 4.0 in Morocco's irrigated sector may therefore be the river-basin agencies themselves.

Proposition 2 (Governance value of monitoring, a conditional hypothesis). *In a groundwater-dependent irrigated system where enforcement is weak for lack of information, and provided that allocation rules exist and the authorities are willing to apply them, the social return to public investment in digital monitoring of water use is expected to exceed the social return to subsidising on-farm digital efficiency, because monitoring relaxes the binding constraint, the unenforceability of caps, whereas efficiency subsidies without enforceable caps may tighten it.*

The proposition is derived from the framework, not measured, and it has clear limits: monitoring lowers the cost of enforcement but does not create the will to enforce. It would not hold if monitoring were costly relative to the value of the water it helps to save, if allocations remained unenforced whatever the information available, or if farmers did not trust the data; its quantitative assessment remains to be done. Nor does it imply that on-farm efficiency is undesirable: once an allocation binds, efficiency lets farmers obtain more output from their entitlement. The point concerns sequencing and the use of public funds.

Two further conditions matter. The first is legitimacy: monitoring is more likely to be accepted when it serves rules that users helped design. Morocco's first aquifer contract, signed for the Souss in 2006, shows the limits of participation without enforcement, since its voluntary nature limited participation and unclear institutional roles prevented its oversight (Closas & Villholth, 2016). The second is data governance: farmers' concerns are procedural and distributional (Jakku et al., 2019; Wiseman et al., 2019), and the aggregation of farm data by agribusinesses creates a power asymmetry (Carbonell, 2016). Law 09-08 on personal data (Kingdom of Morocco, 2009) is a starting point, but collective and remotely sensed agricultural data raise questions it was not designed to answer.

Water-use data collected for allocation purposes should therefore be protected by a specific legal regime that states their purpose, access and retention, and returns them to farmers in a usable form. Such a regime is a condition of adoption rather than a regulatory afterthought, since both monitoring and advisory services depend on farmers' willingness to share data.

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7. THE RAINFED SECTOR: AGRICULTURE 4.0 AS RISK INFORMATION

On rainfed land, the dominant source of output variation is the weather, not the farmer's use of inputs, and adoption barriers are at their most severe. An adoption-centred policy transplanted from the irrigated sector would struggle to find either adopters or returns. The value of digital technology lies elsewhere: in knowing when and how badly the harvest will fail, and in transferring the resulting risk.

Harvest forecasting is the first application. Regression models combining vegetation indices, rainfall and temperature have been used to forecast Moroccan wheat yields before harvest at provincial and national levels (Balaghi et al., 2008), and satellite-based phenology models track observed yields reasonably well (Benabdelouahab et al., 2021). Since the agricultural trade balance deteriorates sharply in dry years (Laator & El Alaoui, 2026a), an early forecast allows import tenders, storage and budget provisions to be decided before world prices move. Index insurance is the second: take-up has remained low without large and sustained subsidies, and better measurement technology is one way of relaxing that constraint (Carter et al., 2017). Morocco already offers, through the mutual insurer MAMDA and with a state contribution to the premium, a multi-risk climate insurance product for cereals and legumes whose basis risk better indices could reduce. Low-cost advisory on a few climate-sensitive decisions, such as sowing date or fertiliser use in a dry season, is the third (Fabregas et al., 2019).

The link to food security should be stated explicitly, because it runs through several steps. Earlier and more accurate harvest forecasts allow earlier import, storage and budget decisions; earlier decisions can secure cereal supplies on better terms and keep domestic availability steadier in drought years; and steadier availability, if import costs are lower or less volatile, supports more stable consumer prices and thus access to food. For Morocco, only the first step, the technical feasibility of forecasting, is documented by the studies cited here; the rainfall sensitivity of the trade balance is documented by the authors' earlier work; the remaining steps are expected effects that would need to be tested.

In all three applications, the principal beneficiary is a public agency or an insurer. Wheat yields can be estimated with good accuracy under Morocco's semi-arid conditions (Bregaglio et al., 2015), so the technical basis of a forecasting system largely exists; what is missing is its integration into

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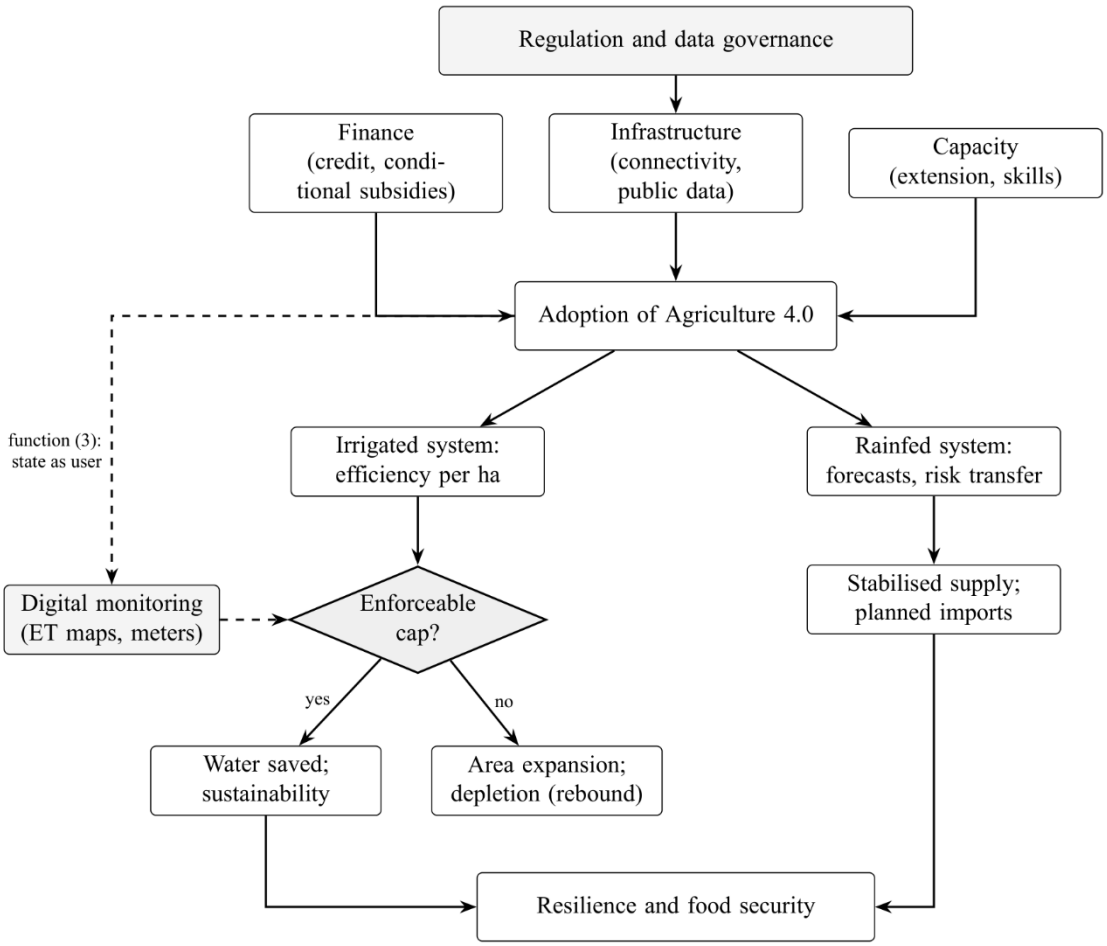
import planning and insurance design. As in the irrigated sector, the decisive user of Agriculture 4.0 is the state.

Proposition 3 (Risk-information value in rainfed systems). *In a rainfed system in which output is governed primarily by rainfall and imports rise to fill the domestic shortfall, the food-security contribution of Agriculture 4.0 runs mainly through forecasting, early warning and risk transfer rather than through on-farm yield gains; its principal users are public agencies and insurers.*

8. AN INTEGRATED POLICY FRAMEWORK

Policy discussions of Agriculture 4.0 commonly group instruments under five headings: financial incentives, regulation, digital infrastructure, capacity building and the integration of sustainability objectives (e.g., Parra-López & Carmona-Torres, 2026). The framework retains all five with two modifications. Sustainability is treated not as a fifth lever but as a condition governing how the others are deployed, and the content of each lever differs between the irrigated and rainfed systems. Figure N°2 presents the theoretical research model of the article. It links the policy levers to adoption, and adoption to outcomes through two channels: in the irrigated system, the effect of adoption on sustainability passes through an enforceable cap, which digital monitoring makes cheaper to enforce (Propositions 1 and 2); in the rainfed system, it passes through forecasting and risk transfer (Proposition 3). Table N°3 translates the model into a policy matrix.

Figure N°2 : Theoretical research model: policy levers, adoption and the enforceable-cap condition



Source: Authors. In the irrigated system, the effect of adoption on sustainability passes through an enforceable cap on water use; digital monitoring lowers the cost of enforcing it. In the rainfed system, value runs through forecasting and risk transfer.

In the irrigated system, the financial lever becomes explicitly conditional, in line with the conclusion that real savings require instruments that track depletion and reallocate water rather than technology subsidies alone (Pérez-Blanco et al., 2020; Ward & Pulido-Velázquez, 2008). Some technologies should not be subsidised at all where caps are absent: solar pumping brings the marginal energy cost of abstraction close to zero, and its promoters have been urged to monitor abstraction and target subsidies accordingly (Closas & Rap, 2017). For small holdings, much of the value of Agriculture 4.0 can be delivered as a service, through a drone diagnostic, a satellite-based advisory or a cooperative sensor network, which mitigates the risk that data-driven farming

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widens the gap between large and small farms (Mehrabi et al., 2021). Treating agro-climatic and remote-sensing data as public infrastructure lowers entry costs for service providers and counters market concentration (Birner et al., 2021).

Responsibility for the levers is spread across institutions, which is one reason why they are rarely coordinated: the Ministry of Agriculture and the Agricultural Development Fund for financial incentives; the river-basin agencies for allocation, metering and water accounting; the national data-protection commission (CNDP) for the rules on data; the telecommunications regulator for rural coverage; the National Office for Agricultural Advice and farmer organisations for advisory services; and MAMDA, with state support, for climate insurance. The framework implies that the conditionality of efficiency subsidies be decided jointly by the first two.

The sustainability lever of Table N°3 changes the metric of success. In the irrigated system, a programme succeeds if consumptive water use at aquifer level falls, not if the equipped area grows; in the rainfed system, it succeeds if the variability of supply and income declines, not if average yields rise in good years.

Table N°3 : Policy matrix: the five levers in Morocco's two agricultural systems

Lever	**Irrigated system (water-constrained)**	**Rainfed system (risk-constrained)**
Financial incentives	Efficiency subsidies conditional on metering and an individual allocation; no subsidy for equipment lowering the marginal cost of abstraction where caps are not enforced	Premium subsidies for index insurance; co-financing of advisory services; credit guarantees for shared-service providers
Regulation	Legal basis for remote sensing in allocation; meter standards; rules for water-use data	Agricultural data ownership and portability; transparency of insurance indices
Infrastructure	Basin water accounting combining satellite, meter and energy data, open to user associations	Rural mobile coverage; national yield forecasting; public agro-climatic data

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Lever	Irrigated system (water-constrained)	Rainfed system (risk-constrained)
Capacity building	Training of basin-agency staff; co-design of allocation rules with users	Advisory through extension services and farmer organisations
Sustainability integration	Enforceable cap as a precondition for efficiency subsidies; evaluation in consumptive use	Evaluation in stability of supply and income, not average yield

Source: Authors.

9. SEQUENCING, RISKS AND EVALUATION

The framework reverses the usual order of operations in the irrigated sector: first build monitoring capacity and its legal basis, then establish allocations, ideally co-designed with users, and only then support on-farm efficiency conditionally on the allocation. In the rainfed sector, public data and forecasting come first, insurance and advisory services second, and individual equipment only where a return has been demonstrated. Each step has costs and prerequisites, such as meters and their maintenance, the validation of remote-sensing data and the staff capacity of basin agencies, which should be budgeted before efficiency subsidies are made conditional on them.

Three risks run through the framework. The first is capture: digital agriculture is driven mainly by private firms, with well-founded concerns about the market power of large agribusiness (Birner et al., 2021), so subsidising proprietary systems without interoperability requirements may create costly dependencies. The second is exclusion: if benefits accrue mainly to large, connected, irrigated holdings, digitalisation will deepen the dualism of Moroccan agriculture (Klerkx & Rose, 2020; Mehrabi et al., 2021); monitoring itself imposes compliance costs that weigh more on small holdings, which argues for publicly funded meters and simple reporting for them. The third is labour displacement: field evidence from North America points to a bifurcation of farm labour into high-skill and low-skill segments (Rotz et al., 2019).

Finally, adoption rates measure inputs to policy, not outcomes. The relevant outcomes are consumptive water use at aquifer level in the irrigated sector and the stability of supply and income in the rainfed sector. Aggregate time series are often too short and noisy to detect policy effects of plausible size, so evaluation should be designed ex ante, with staggered roll-out where feasible and an explicit assessment of statistical power before any conclusion is drawn from a null result.

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Indicators should also be disaggregated by farm size, by farming system and by access to digital services, so that the distributional risks discussed above can be tracked: for instance, the distribution of subsidies by holding size, the share of small holdings using advisory or insurance services, and mobile coverage of rainfed farming areas. Table N°4 separates what the article documents from what it proposes, and associates each proposition with indicators and a possible test.

Table N°4 : From propositions to empirical tests

Proposition	**Status in this article**	**Indicators**	**Possible test (subject to a data audit)**
P1. Conditionality of sustainability gains	Mechanism derived from accounting identities; consistent with international evidence and Moroccan field studies; not tested here	Irrigated area, crop mix, consumptive use (satellite ET), piezometric levels	Compare aquifers or perimeters with and without enforced caps, before and after efficiency subsidies
P2. Governance value of monitoring	Conditional hypothesis; not quantified	Metered volumes, piezometric trends, enforcement actions, monitoring costs	Exploit a staggered roll-out of metering across aquifers, if it can be documented
P3. Risk-information value in rainfed systems	First link (feasibility of forecasting) documented; later links expected	Forecast lead time and error; timing of cereal imports; cereal import dependency ratio; variability of domestic cereal availability; volatility of flour and bread prices	Event study of import decisions and prices around forecast releases in drought years

Source: Authors. The tests are indicative; whether a credible identification strategy exists can only be judged after an audit of the available data.

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CONCLUSION

This article set out to design a policy framework that would allow Morocco to accelerate the adoption of Agriculture 4.0 without accelerating the depletion of its water resources. On the theoretical side, it combined three bodies of theory. The economics of technology adoption shows that low adoption justifies public intervention only where private and social returns diverge. The rebound effect, applied to irrigation, shows that a technology which lowers the private cost of using water can raise its aggregate use when the irrigated area or crop water use can expand. The theory of common-pool resources shows that a resource can be governed only if its use can be monitored. Together, these theories yield a theoretical research model in which the effect of adoption on sustainability passes through an enforceable cap in the irrigated system and through forecasting and risk transfer in the rainfed system.

On the methodological side, the article relied on two accounting identities that separate withdrawals from consumptive use, on descriptive FAOSTAT land-use series, and on a purposive synthesis of peer-reviewed studies, policy documents and legal texts, each checked against bibliographic records. On the empirical side, the evidence is descriptive and indirect but consistent: international studies indicate that efficiency subsidies have not reduced water use where irrigated area could expand; Moroccan field studies document the same pattern for drip irrigation and solar pumping, alongside groundwater declines of 20 to 65 metres; and FAOSTAT data show that the olive area alone has expanded by the equivalent of 50 to 101 per cent of the increase in equipped area depending on the years compared (77 per cent with five-year averages), while the cereal area has fallen since the 2000s.

Three propositions follow. Subsidising efficiency without an enforceable cap can increase resource use; in the irrigated sector, the largest public return to Agriculture 4.0 is expected from monitoring, which is a necessary but not sufficient condition for enforceable allocation; and in the rainfed sector, the contribution of digital tools to food security runs mainly through forecasting and risk transfer. The resulting framework keeps the five conventional policy levers but makes them conditional, sequenced and differentiated. Its main limitation is that it is conceptual: the propositions are derived, not measured. Table N°4 associates each of them with indicators and a possible test, and their empirical assessment, beginning with the effect of monitoring on abstraction in Moroccan aquifers and with the share of public subsidies that finances wells and pumps, is the

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natural next step. Accelerating Agriculture 4.0 is a worthwhile objective; the task of policy is to ensure that it does not accelerate depletion along with it.

Declaration of generative AI use: A large language model (Claude, Anthropic) was used to assist in drafting the text and in checking bibliographic references against Crossref and publishers' records. The authors reviewed and revised all content and take full responsibility for it.

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