International Scholars Journals

African Journal of Agronomy ISSN: 2375-1185 Vol. 14 (12), pp. 001-006, December, 2026. Available online at www.internationalscholarsjournals.org © International Scholars Journals

Author(s) retain the copyright of this article.

Research Article

Precision Irrigation and Deficit Irrigation for Water-Limited Cropping Systems: Physiology, Scheduling, and Farmer-Scale Decisions

Fatima A. Bello[1], James K. Whitfield[2], Ananya Deshmukh[3], Carlos M. Herrera[4], Ingrid S. Johansson[5], Daniel T. Osei[6]

[1]*Department of Crop Production, Ahmadu Bello University, Zaria, Nigeria*
[2]*Department of Plant Sciences, University of California, Davis, Davis, USA*
[3]*Department of Agronomy, University of Agricultural Sciences, Bengaluru, India*
[4]*Facultad de Agronomía, Universidad de Buenos Aires, Buenos Aires, Argentina*
[5]*Department of Crop Production Ecology, Swedish University of Agricultural Sciences, Uppsala, Sweden*
[6] *Department of Soil and Irrigation Research, University of Ghana, Legon, Ghana. Corresponding author: Fatima A. Bello, fatima.bello@abu.edu.ng*

Received: 5 September 2026 | Revised: 18 October 2026 | Accepted: 2 November 2026 | Published: 3 December 2026

Abstract

Water scarcity is now the principal limit to crop production across many irrigated and rain-fed landscapes. Rising evaporative demand, competing demands for water, groundwater depletion, and increasingly erratic rainfall mean that producing more food per drop has become as important as producing more food per hectare. This article reviews precision irrigation and deficit irrigation as complementary agronomic strategies for water-limited cropping systems. It explains how crops respond to water deficit at different growth stages, how regulated deficit irrigation, partial root-zone drying, alternate wetting and drying, drip irrigation, and improved scheduling change the balance among yield, water productivity, quality, and soil salinity, and how soil, weather, crop, and socioeconomic conditions determine which strategy is appropriate. The synthesis shows that deficit strategies can raise water productivity substantially when stress is imposed at tolerant stages and avoided at sensitive stages, but that the same deficit imposed at flowering can cause disproportionate yield loss. Precision scheduling, soil moisture monitoring, remote sensing, and simple decision rules can reduce over-irrigation and improve timing, yet their benefits depend on reliable water delivery, affordable sensors, maintenance, and advice that farmers can act on. The article proposes a field-scale decision framework that links water accounting, crop stage, soil water storage, salinity risk, and household objectives, and it identifies research and policy priorities for scaling water-smart irrigation without deepening inequity in access to water.

Keywords: deficit irrigation; precision irrigation; water productivity; crop water stress; drip irrigation; irrigation scheduling; salinity; water-limited agriculture

1. Introduction

Irrigated agriculture produces a disproportionate share of the world's food from a relatively small share of cultivated land, yet it also accounts for a large share of freshwater withdrawals (FAO, 2020; Molden et al., 2010). In many basins, withdrawals have exceeded sustainable limits, groundwater levels have fallen, and competition among agriculture, cities, industry, and ecosystems has intensified. Climate change adds a further layer of stress: higher temperatures increase crop water demand, rainfall becomes more variable, and dry spells within the rainy season become more damaging even when seasonal totals appear normal (IPCC, 2022; Challinor et al., 2014). For agronomists, the central question has therefore shifted. It is no longer only how to supply enough water to maximise yield in a single field, but how to allocate a limited and uncertain water supply across fields, crops, and seasons to maximise food, income, and resilience while protecting soils and aquifers.

Precision irrigation and deficit irrigation offer two complementary answers. Precision irrigation seeks to apply the right amount of water at the right time and place, using better measurement, scheduling, and delivery systems. Deficit irrigation deliberately applies less water than full crop evapotranspiration demand, accepting a controlled yield reduction in exchange for higher water productivity, expanded irrigated area, or water saved for a later, more

sensitive growth stage (English, 1990; Fereres and Soriano, 2007). Both approaches require a clear understanding of crop physiology, soil water storage, weather, and the economics of water. Without that understanding, deficit irrigation can easily become simply under-irrigation, and precision equipment can become an expensive way to deliver water at the wrong time.

This article reviews the physiological basis of crop response to water deficit, the main deficit and precision strategies, their evidence across crops and environments, and the practical decisions farmers and irrigation managers must make. It gives particular attention to smallholder and water-scarce contexts, where water delivery is often unreliable, fields are fragmented, and labour and cash constraints shape what is feasible.

2. Crop Water Relations: Why Timing Matters More Than Totals

Crop yield is closely related to transpiration because stomata must open to take up carbon dioxide, and water is lost in the process. When soil water becomes limiting, roots signal the shoot through hormones such as abscisic acid, stomata close, photosynthesis declines, leaf expansion slows, and assimilate partitioning changes (Chaves et al., 2003; Blum, 2011). Mild stress during vegetative growth may reduce leaf area and plant height with only a modest effect on final grain yield if water is restored before reproductive development. Severe stress at flowering, by contrast, can reduce pollen viability, silk emergence, fertilisation, and grain number, and grain number is often the main determinant of cereal yield (Boyer and Westgate, 2004; Farooq et al., 2009). Stress during grain filling shortens the filling period and reduces grain weight, while stress at maturity has a smaller effect on yield but can affect quality and harvest operations.

These stage differences explain why a single seasonal water total is a poor predictor of yield. Two fields that receive the same total water can produce very different yields depending on when deficits occur. Maize is especially sensitive around tasselling and silking because of the synchrony required between pollen shed and silk emergence (Boyer and Westgate, 2004). Wheat is sensitive at anthesis and early grain filling, when grain number and grain weight are established. Rice is sensitive to water deficit at panicle initiation and flowering, although alternate wetting and drying can be managed to avoid severe stress at those stages (Bouman, 2007; Carrijo et al., 2017). Legumes can be sensitive at flowering and pod filling, when flower abortion and pod loss reduce seed number. Figure 2 summarises this general pattern for maize and wheat and provides the physiological logic for regulated deficit irrigation: protect the sensitive window, and save water where the crop can tolerate it.

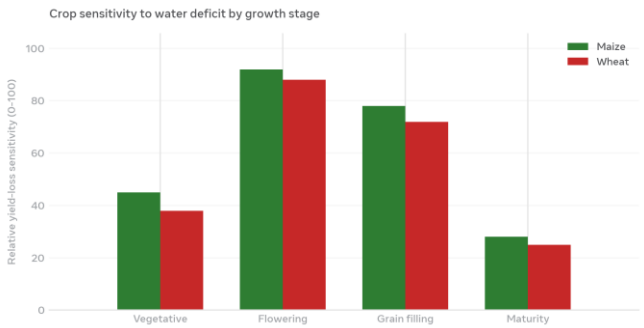

Figure 2. Crop sensitivity to water deficit by growth stage for maize and wheat, based on synthesis of the physiological literature cited in the text. Flowering is the most sensitive stage.

3. Deficit Irrigation Strategies

Regulated deficit irrigation imposes a planned water deficit during a tolerant growth stage while maintaining near-full irrigation during sensitive stages (Fereres and Soriano, 2007; English, 1990). In fruit and vine crops, regulated deficit can also improve quality, for example by increasing sugar concentration and colour, although the same deficit can reduce fruit size if imposed too severely or at the wrong time (Chaves et al., 2010). In cereals, the most reliable form of regulated deficit is to reduce irrigation during early vegetative growth, allow the crop to develop a deeper root system, and then restore water before flowering. The yield penalty is often small, while water saved can be used to irrigate additional land or to protect a later crop.

Partial root-zone drying alternates irrigation between sides of the root system. One side remains wet while the other dries, generating root signals that partially close stomata and reduce transpiration while maintaining plant water status better than uniform drying (Davies and Zhang, 1991; Kang and Zhang, 2004). In practice, partial root-zone drying requires two drip lines or furrows and careful alternation. Meta-analyses and reviews report that it can improve water-use efficiency, but yield effects vary by crop, soil, climate, and the severity and duration of drying (Kang and Zhang, 2004; Dodd, 2009). It is most promising where drip infrastructure already exists and where water is expensive or strictly allocated.

Alternate wetting and drying is a rice-specific strategy in which the field is allowed to dry to a defined soil water level before re-flooding, rather than being kept continuously flooded (Bouman, 2007; Carrijo et al., 2017). A meta-analysis found that alternate wetting and drying could reduce water use substantially with only a small average yield penalty, and could reduce methane emissions because soils are aerated during dry periods (Carrijo et al., 2017; Linquist et al., 2015). Success depends on field levelling, reliable water control, and careful monitoring so that the soil does not dry below the safe threshold during sensitive stages. On poorly levelled fields or where water delivery is unpredictable, farmers may rationally keep fields flooded as insurance against a missed irrigation.

4. Precision Irrigation: Delivery, Sensing, and Scheduling

Precision irrigation has three linked components: delivery, measurement, and decision-making. Delivery systems differ in uniformity, evaporation losses, and suitability for different crops and soils. Drip irrigation delivers water directly to the root zone, reduces evaporation and runoff, and allows fertigation, but it requires clean water, filtration, maintenance, and capital investment (Lamm et al., 2007; Ayars et al., 2007). Sprinkler systems are more flexible across crops and can be moved, but wind and evaporation can reduce uniformity. Surface irrigation remains dominant in many regions because it is simple and cheap, but it can be improved substantially through land levelling, gated pipes, surge flow, and better scheduling (FAO, 2020).

Measurement has advanced rapidly. Soil moisture sensors, tensiometers, and capacitance probes provide

continuous information on soil water status, while weather stations and satellite estimates of evapotranspiration provide information on atmospheric demand (Jones, 2004; Mulla, 2013). Canopy temperature, measured with infrared thermometers or thermal imagery, can indicate crop water stress before visible wilting because stressed leaves close stomata and warm relative to well-watered leaves (Jones, 2004; Bellvert et al., 2014). Remote sensing can map spatial variability in canopy vigour, soil moisture, and crop coefficient across large schemes. The challenge is not the absence of data, but the translation of data into a simple, timely irrigation decision that matches the farmer's water allocation, labour availability, and pump schedule.

Scheduling rules should therefore be as simple as the context allows. A water-balance approach estimates soil water depletion from crop evapotranspiration, rainfall, and irrigation, and triggers irrigation when depletion reaches a crop- and stage-specific threshold. A soil-moisture threshold approach irrigates when sensor readings fall to a defined value. A plant-based approach uses canopy temperature or leaf water potential. In many smallholder systems, a practical hybrid works best: a seasonal calendar based on crop stage and typical weather, adjusted by a simple soil-moisture check, a look at the forecast, and knowledge of when the next water delivery is expected (FAO, 2020; Hansen et al., 2019).

5. Soil, Salinity, and Nutrient Interactions

Water management cannot be separated from soil management. Soil texture, structure, organic matter, and depth determine how much water a soil can store and how quickly it can be taken up by roots. Sandy soils drain rapidly and need frequent, small irrigations, while clay soils store more water but may suffer from poor aeration and slow infiltration. Soil organic matter improves aggregation, infiltration, and plant-available water, so practices that build organic matter, such as residue retention, compost, and cover crops, complement precision irrigation (Lal, 2004; Blanco-Canqui and Ruis, 2018). Compacted layers restrict root depth and reduce the effective soil water reservoir, making crops more vulnerable to short dry spells even when total soil water appears adequate.

Salinity is a major risk in water-limited irrigation. When irrigation water contains salts and leaching is insufficient, salts accumulate in the root zone and reduce water uptake, even when the soil appears wet (Ayers and Westcot, 1985; Rhoads, 1992). Deficit irrigation can worsen salinity if it reduces the leaching fraction below what is needed to move salts below the root zone. Farmers therefore need to know the electrical conductivity of irrigation water and soil, and to plan occasional leaching irrigations where salinity is a risk. Drip irrigation can help by keeping salts at the edge of the wetted zone, but it requires careful emitter placement and periodic flushing. Nutrient management also interacts with water: nitrogen applied before a heavy irrigation can be leached, while fertigation through drip can improve nutrient synchrony and reduce losses (Bali et al., 2018; Snyder et al., 2009).

6. Evidence Across Crops and Environments

Evidence on deficit and precision irrigation is consistent on one point: water productivity can be raised, but yield outcomes depend on crop, stage, severity, and environment (Fereres and Soriano, 2007; Geerts and Raes, 2009). A widely cited synthesis of deficit irrigation in water-scarce regions found that water productivity increased in most cases, while yield penalties were modest when deficits were moderate and carefully timed, and large when deficits were severe or imposed at sensitive stages (Geerts and Raes, 2009). For wheat, moderate deficit during vegetative growth and careful restoration at anthesis often produced the best balance between water saving and yield. For maize, protecting the flowering window was more important than total seasonal water. For cotton and sunflower, moderate deficit could be tolerated with relatively small yield loss, while for rice, alternate wetting and drying offered a practical compromise between water saving and yield stability (Carrijo et al., 2017; Bouman, 2007).

Drip irrigation has shown large water savings and yield gains in vegetables, orchards, and high-value crops, where the value of water and produce justifies investment (Lamm et al., 2007; Ayars et al., 2007). In staple cereals, the economics are less favourable because margins are lower and fields are larger, so low-cost drip, improved surface irrigation, and better scheduling often deliver more value per unit of investment. Solar-powered pumps have expanded access to irrigation in some regions, but they can also accelerate groundwater depletion if pumping is not governed by allocation rules and monitoring (FAO, 2020). Figure 1 summarises the general pattern from the cited syntheses: precision and deficit strategies tend to raise water productivity more than they raise yield, and the largest gains occur where baseline scheduling was poor.

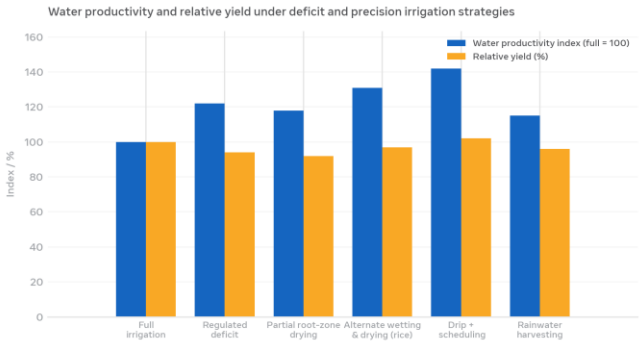

Figure 1. Water productivity and relative yield under deficit and precision irrigation strategies, based on synthesis of the meta-analyses and reviews cited in the text. Values vary by crop, soil, climate, and management.

7. Economics, Equity, and Adoption

Adoption of precision and deficit irrigation is shaped by water rights, energy costs, labour, and risk. A farmer who pays by volume has a direct incentive to save water, while a farmer who pays a flat fee or receives water on a fixed rotation may have little incentive to save it, even if the technology is available. A farmer who receives water unpredictably may keep fields wet as insurance, even if that wastes water, because the cost of a missed irrigation at flowering can exceed the cost of over-irrigation in a normal week. These incentives explain why technically sound recommendations often fail when institutional arrangements are ignored (Molden et al., 2010; FAO, 2020).

Equity deserves explicit attention. Drip systems, sensors, and solar pumps can improve productivity for those who can afford them, but they can also widen gaps between large and small farmers, men and women, and head- and tail-end users in a canal system. Tail-end users often receive less and later

water, and they may be the least able to invest in storage or pumps. Women farmers may have less secure access to land and water, less control over irrigation decisions, and less access to extension and credit, even when they provide much of the labour (Farnworth et al., 2017; Huyer et al., 2015). Programmes that subsidise equipment without addressing water allocation, maintenance, and training may therefore produce impressive demonstration plots and disappointing system-wide outcomes. Farmer-managed comparisons, water-user associations, and transparent allocation rules are essential complements to technology.

8. A Field-Scale Decision Framework

A practical framework for water-limited fields can be stated in six steps. First, account for water: how much water is available, when, at what cost, and with what reliability? Second, characterise the field: soil texture, depth, salinity, slope, and water storage. Third, identify the crop and its sensitive stages, and choose varieties with appropriate duration and drought tolerance. Fourth, select a strategy that matches water availability to crop sensitivity, for example full irrigation at flowering, moderate deficit during vegetative growth, and alternate wetting and drying for rice where water control allows. Fifth, set a simple scheduling rule, using soil moisture, weather, and crop stage, and record water applied, rainfall, and yield. Sixth, review after the season: did water productivity improve, did yield stability improve, did salinity change, and was labour and cost acceptable? Table 1 summarises these choices, while Table 2 proposes indicators for monitoring.

This framework is deliberately iterative. A farmer may begin with a low-cost improvement, such as land levelling and a soil-moisture check, before investing in drip or sensors. A water-user association may begin with better rotation schedules and measurement of deliveries before investing in canal lining or pressurised systems. The goal is not to adopt the most advanced technology, but to make the next water decision measurably better than the last one.

Tables

Table 1. Field-scale decisions for precision and deficit irrigation.

Decision	Key question	Practical action
Water accounting	How much, when, how reliable?	Record allocation, pump hours, rainfall
Field diagnosis	Soil, salinity, storage?	Test EC, check depth, compaction
Crop choice	Sensitive stages?	Match variety duration to water window
Strategy	Where to save water?	Protect flowering, deficit in vegetative stage
Scheduling	When to irrigate?	Soil moisture + forecast + stage rule
Review	Did it pay?	Compare water productivity, yield, cost

Table 2. Indicators for monitoring precision and deficit irrigation.

Dimension	Indicator	Practical measurement
Water productivity	kg grain per m3 water	Yield divided by irrigation + rainfall
Yield stability	CV across seasons	Multi-season records
Soil salinity	Electrical conductivity	Soil and water EC tests
Labour and cost	Hours and cost per hectare	Farmer records
Equity	Water received by head vs tail	Delivery records, association data
Environment	Groundwater level, runoff	Well observations, field notes

9. Future Research and Policy Priorities

Future research should report water, yield, quality, salinity, labour, and cost together, rather than yield alone. Long-term trials are needed to assess whether repeated deficit irrigation changes soil salinity, root depth, and organic matter over several seasons. Research on low-cost sensors, simple scheduling tools, and local calibration is more valuable for smallholders than further development of expensive, data-heavy systems that require constant connectivity (Fabregas et al., 2019; Hansen et al., 2019). Breeding for drought tolerance should be evaluated under deficit and precision irrigation, not only under full irrigation, because genotype-by-water-management interactions can change variety rankings (Challinor et al., 2014; Ceccarelli, 2015). Remote sensing and machine learning can improve large-scale water accounting, but they must be validated against ground measurements and made accessible to irrigation managers and farmer groups.

Policy should align water pricing, energy pricing, and allocation rules with water-saving goals. Subsidies for drip and solar pumps should be paired with water metering, allocation limits, and maintenance support, otherwise they can increase total water use by expanding irrigated area. Public investment in canal maintenance, measurement, weather services, soil testing, and extension is often more cost-effective than subsidising equipment alone (FAO, 2020; Molden et al., 2010). Water-user associations need clear rights, transparent schedules, and mechanisms to resolve disputes. Finally, policy should protect environmental flows and groundwater, because a strategy that raises farm-level water productivity while depleting an aquifer is not sustainable at basin scale.

10. Conclusion

Precision irrigation and deficit irrigation are not substitutes for good agronomy; they are ways to make good agronomy possible when water is scarce. Their success depends on

respecting crop physiology, especially the sensitivity of flowering, on measuring soil water and weather, on managing salinity and nutrients, and on aligning incentives, water rights, and advice with farmers' real constraints. When stress is imposed at tolerant stages, avoided at sensitive stages, and supported by reliable delivery and simple scheduling, water productivity can rise substantially with only modest yield loss. When the same stress is imposed blindly, or when technology is promoted without attention to equity and maintenance, the result can be lower yield, saltier soil, and wider gaps between farmers. The priority for the December 2026 season and beyond is therefore practical: account for water, protect the sensitive window, measure the next irrigation, and learn from each season.

Acknowledgements

The authors thank farmers, irrigation managers, and water-user associations whose practical experience informs this synthesis. No external funding was received for this review.

Conflict of Interest

The authors declare no conflict of interest.

References

Ayars, J.E., Phene, C.J., Hutmacher, R.B., et al. (2007). Subsurface drip irrigation of row crops: A review of 15 years of research at the Water Management Research Laboratory. Agricultural Water Management, 90(1-3), pp. 1-26.

Ayers, R.S. and Westcot, D.W. (1985). Water Quality for Agriculture. FAO Irrigation and Drainage Paper 29. Rome: FAO.

Bali, S.K., et al. (2018). A review of methods to improve nitrogen use efficiency in agriculture. Sustainability, 10(1), p. 51.

Bellvert, J., Marsal, J., Girona, J. and Zarco-Tejada, P.J. (2014). Seasonal evolution of crop water stress index in grapevine. Agricultural Water Management, 140, pp. 55-63.

Blanco-Canqui, H. and Ruis, S.J. (2018). No-tillage and soil physical environment. Geoderma, 326, pp. 164-200.

Blum, A. (2011). Plant Breeding for Water-Limited Environments. New York: Springer.

Bouman, B.A.M. (2007). A conceptual framework for the improvement of crop water productivity at different spatial scales. Agricultural Systems, 93(1-3), pp. 43-60.

Boyer, J.S. and Westgate, M.E. (2004). Grain yields with limited water. Journal of Experimental Botany, 55(407), pp. 2385-2394.

Carrijo, D.R., Lundy, M.E. and Linquist, B.A. (2017). Rice yields and water use under alternate wetting and drying irrigation: A meta-analysis. Field Crops Research, 203, pp. 173-180.

Ceccarelli, S. (2015). Efficiency of plant breeding. Crop Science, 55(1), pp. 87-97.

Challinor, A.J., et al. (2014). A meta-analysis of crop yield under climate change and adaptation. Nature Climate Change, 4(4), pp. 287-291.

Chaves, M.M., Maroco, J.P. and Pereira, J.S. (2003). Understanding plant responses to drought. Functional Plant Biology, 30(3), pp. 239-264.

Chaves, M.M., et al. (2010). Grapevine under deficit irrigation. Annals of Applied Biology, 157(3), pp. 293-308.

Davies, W.J. and Zhang, J. (1991). Root signals and the regulation of growth and development of plants in drying soil. Annual Review of Plant Physiology and Plant Molecular Biology, 42, pp. 55-76.

Dodd, I.C. (2009). Rhizosphere manipulations to maximize crop productivity. Plant and Soil, 318, pp. 245-264.

English, M. (1990). Deficit irrigation. I: Analytical framework. Journal of Irrigation and Drainage Engineering, 116(3), pp. 399-412.

Fabregas, R., Kremer, M. and Schilbach, F. (2019). Realizing the potential of digital development: The case of agricultural advice. Science, 366(6471), eaay3038.

FAO (2020). The State of Food and Agriculture 2020: Overcoming Water Challenges in Agriculture. Rome: FAO.

Farooq, M., Wahid, A., Kobayashi, N., Fujita, D. and Basra, S.M.A. (2009). Plant drought stress: Effects, mechanisms and management. Agronomy for Sustainable Development, 29(1), pp. 185-212.

Farnworth, C.R., et al. (2017). Gender and climate-smart agriculture. In: Huyer, S. et al. eds. Gender, Climate Change and Agriculture. Wallingford: CABI, pp. 1-18.

Fereres, E. and Soriano, M.A. (2007). Deficit irrigation for reducing agricultural water use. Journal of Experimental Botany, 58(2), pp. 147-159.

Geerts, S. and Raes, D. (2009). Deficit irrigation as an on-farm strategy to maximize crop water productivity in dry areas. Agricultural Water Management, 96(9), pp. 1275-1284.

Hansen, J.W., et al. (2019). Climate services can support African farmers' adaptation. Nature Climate Change, 9, pp. 747-753.

Huyer, S., et al. (2015). Gender and climate change in agriculture. CCAFS Working Paper. Copenhagen: CGIAR.

IPCC (2022). Climate Change 2022: Impacts, Adaptation and Vulnerability. Cambridge: Cambridge University Press.

Jones, H.G. (2004). Irrigation scheduling: Advantages and pitfalls of plant-based methods. Journal of Experimental Botany, 55(407), pp. 2427-2436.

Kang, S. and Zhang, J. (2004). Controlled alternate partial root-zone irrigation. Agricultural Water Management, 69(3), pp. 191-198.

Lal, R. (2004). Soil carbon sequestration impacts on global climate change and food security. Science, 304(5677), pp. 1623-1627.

Lamm, F.R., Ayars, J.E. and Nakayama, F.S. (2007). Microirrigation for Crop Production. Amsterdam: Elsevier.

Linquist, B.A., et al. (2015). Greenhouse gas emissions and water use in rice systems. Field Crops Research, 183, pp. 243-254.

Molden, D., et al. (2010). Improving agricultural water productivity. Agricultural Water Management, 97(4), pp. 527-542.

Mulla, D.J. (2013). Twenty five years of remote sensing in precision agriculture. Biosystems Engineering, 114(4), pp. 358-371.

Rhoads, J.D. (1992). Salinity: Electrical conductivity and total dissolved solids. In: Page, A.L. ed. Methods of Soil Analysis, Part 2. Madison: ASA-SSSA, pp. 417-435.

Snyder, C.S., Bruulsema, T.W., Jensen, T.L. and Fixen, P.E. (2009). Review of greenhouse gas emissions from crop production systems. Agriculture, Ecosystems & Environment, 133(3-4), pp. 247-266.