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Research Paper

Quantifying the adoption of conservation agriculture: Development and application of the Conservation Agriculture Appraisal Index

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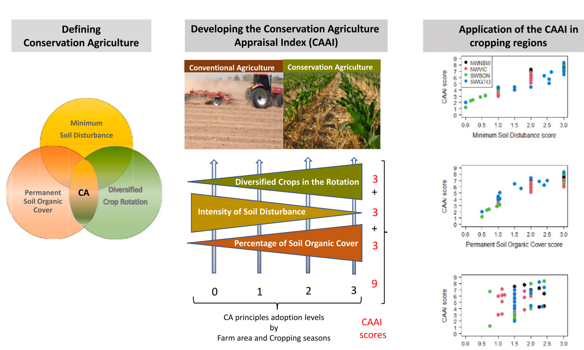
HIGHLIGHTS

- Estimates of conservation agriculture (CA) adoption vary worldwide because of a lack of standardized methodology.
- The novel CA Appraisal Index (CAAI) quantifies concurrent adoption of core CA principles across farm area and cropping seasons.
- The CAAI defines thresholds that determines the intensity of utilization of the core CA principles.
- CAAI was successfully applied to cropping regions in Australia and Mexico to estimate annual CA adoption.
- CAAI can be used as a benchmarking research tool for an appraisal of CA adoption at the farm level.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Estimates of conservation agriculture (CA) adoption vary worldwide because of a lack of a standardized methodology to quantify the simultaneous utilization of its core principles of minimum soil disturbance, permanent soil organic cover and crop diversification. Comparisons of CA adoption among farms across regions requires estimation of the farm area and cropping season where CA principles are applied.
OBJECTIVE: To develop the Conservation Agriculture Appraisal Index (CAAI) as a standardized conceptual framework with defined thresholds that indicates the intensity and frequency of use of each CA core principle. CAAI was subsequently applied to quantify CA adoption on farms across four wheat (*triticum aestivum*) growing regions, both with and without livestock, including dryland and irrigated systems in Australia and Mexico, respectively.
METHODS: CAAI is a continuous scoring system that estimates the intensity and frequency of application of the core principles and their concurrent utilization to assess the extent of CA adoption. CAAI score is the sum of the scores of each core principle, accounting for the percentage of the farm area and cropping season where CA is

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applied. CAAI emerged from semi-structured interviews, questionnaires, and farm visits that captured underlying patterns of CA use in regional-specific contexts.

RESULTS AND CONCLUSIONS: CAAI assessed annual CA adoption on 100 farms in four wheat growing regions with different environments and farming systems. The adoption of CA was higher in Australia than Mexico, where partial adoption was more prevalent, especially for summer crops. 'No adoption' of CA occurred when one of the core principles consistently scored zero within a year.

SIGNIFICANCE: The CAAI can be used as a benchmarking research tool at the farm level to standardize units for comparisons and identify levels of CA adoption by farm area and cropping seasons between and across regions.

1. Introduction

Conservation Agriculture (CA) is promoted as sustainable farming practice that maintains soil health properties, improves water and nutrient efficiency (Lal, 2015) and reduces costs of production. CA is based on three core principles: 1) minimum soil disturbance (soil disturbed area < 15 cm wide or 24% of the cropping area); 2) permanent soil organic cover (at least 30% soil cover with stubble retention or cover crops), and 3) crop diversification with a high incidence of non-cereal crops or break crops, especially legumes (FAO, 2017).

Controlled-traffic farming (CTF) and permanent-raised beds (PB) are complementary practices to CA used in some regions to restrict soil compaction to machinery tram-tracks (Chamen, 2006) and to furrow bottoms in PB (Verhulst et al., 2011).

CA principles are generally applied to cropping systems or the crop component of mixed-farming systems (FAO, 2017). Integrated crop-livestock that incorporates sustainable grazing rates and periods with reduced tillage can avoid soil compaction (Drewry, 2006; Fernández et al., 2015). Additionally, where there are crop-pasture sequences, the absence or reduction of tillage during the pasture phase, along with soil organic cover and the potential for a break-crop effect, indicates that pastures could be also considered in any appraisal of CA adoption.

CA adoption requires simultaneous use of the three core principles (Dumanski et al., 2014; Kassam et al., 2018). The level of interaction of the CA principles impacts the outcome. Its adoption is not fixed but can be intermittent and influenced by exogenous factors including the environment, soil type, farming system, crop species, access to specialized machinery and markets (Wall et al., 2013). Therefore, CA adoption cannot not be assessed using binary approaches.

Other terms have been used interchangeably to refer to CA, such as conservation farming, direct drilling, conservation tillage, minimum till, no-till and zero-till (Dumanski and Peiretti, 2013; Mitchell et al., 2019). Therefore, ambiguities in the approaches used to estimate CA adoption level and areas under CA are evident when all three CA core principles are not considered collectively (Lobb et al., 2007) or different intensities of utilization are identified, either on all or part of the farm area or only in some cropping seasons.

Worldwide rates of adoption of CA vary (Kassam et al., 2018). High CA adoption was reported in pioneer countries like the USA (Egan, 2014), Canada (Awada et al., 2014), Australia (Llewellyn and Ouzman, 2019), Brazil (Bolliger et al., 2006) and Argentina (Peiretti and Dumanski, 2014). In 2008, CA reportedly covered 106 M ha, (7.5% of global cropland) increasing to 180 M ha (12.5% of global cropland) by 2015–16 and 205.4 M ha (14.7% cropland) by 2018–19 (Friedrich et al., 2012; Kassam et al., 2018; Kassam et al., 2022; Kassam et al., 2009). While the USA has the largest area under CA, Argentina has by far the highest percentage of arable land under CA (Appendix A). Other countries in Latin America, Africa and Asia recorded low CA adoption.

The accuracy of CA estimates based on reports by governments, research institutions and farmer organizations (Derpsch et al., 2010; Kassam et al., 2018) is questionable (Giller et al., 2015) and non-comparable due to differences in units of measurement (by farm area, numbers of adopters and the numbers of no-till planters sold) and research projects biases (Brown et al., 2017). Furthermore, it is often unclear whether the core principles were consistently employed when quantifying adoption (Bolliger, 2007).

Previous CA adoption studies of smallholders in Africa were methodologically weak and biased (Andersson and D'souza, 2014; Gattinger et al., 2011), overestimating areas under CA by using only one or two principles of CA to measure adoption (Erenstein et al., 2012; Khataza et al., 2018; Pittelkow, 2015). While several quantitative studies examined the adoption of CA by focusing on agronomic and econometric analysis (Knowler and Bradshaw, 2007; Pannell et al., 2006), very few qualitatively explored the reasons for full, partial or non-use of CA (Hermans et al., 2020).

A standardized framework to assess CA adoption at the farm-level is required for reliable comparisons of the concurrent use of CA core principles over time and across the farm. This framework would enable governments, research agencies, and farmers to assess spatial variation in CA adoption over time. Thus, the impact of varying degrees of CA adoption on farm inputs, soil health parameters and other ecosystem services could be identified for policy interventions and resource allocation (Stavi et al., 2016). This framework must provide a clear definition of CA components, the intensity and frequency at which CA is utilized across the farm area and cropping seasons. Importantly, standardize units must be used for CA cross-regional and cross-country adoption comparisons (Derpsch et al., 2014).

Brown et al. (2017) introduced the Conservation Agriculture Appraisal Framework (CAAF), with well-defined thresholds of each CA principle, to assess the intensity of utilization of each of the three CA principles by plot. Each plot was scored with a plot level index ranging from zero to one. The scores of the three principles per plot were averaged, and the sum of the farm plot scores gave a farm weighted index. While this study showed that CA areas in Africa had been overestimated, they primarily focussed on quantifying legumes as break crop. The authors concluded that qualitative research is needed to understand pathways of CA adoption.

Another study in Canada (Takam Fongang et al., 2023) used a composite index that was first calculated at the plot level and then at the farm level and averaged over three years to measure full, partial and no-adoption of CA principles. However, the index did not discriminate between varying levels of CA intensity because each CA principle was considered a dichotomous variable.

We developed a standardized framework to address the shortcomings of earlier approaches used to assess the adoption of CA in cropping systems with or without livestock. This framework established adoption thresholds and used a scoring system to determine the intensity and frequency of minimum soil disturbance and permanent soil organic cover. Additionally, the new approach accounts for the proportion of break crops, including pastures, and long fallows in crop rotations. This system generates an aggregated CA score ranging from 0 to 9 that reflects the overall level of CA adoption. Our framework quantifies the extent to which the CA is applied by considering both spatial (farm area) and time (cropping season) dimensions.

This study aimed: 1) to develop the Conservation Agriculture Appraisal Index (CAAI) as a conceptual framework and 2) to apply CAAI to assess the adoption of CA on 100 farms in wheat growing regions with heterogeneous environments in Mexico and Australia. Results of annual CAAI scores, for winter and summer seasons, were captured mostly from farms with cropping systems. Some farms included mixed farming and allowed grazing in the cropping area after harvest, while others allowed seasonal grazing by an external enterprise. Pastures were quantified only in the DCR component for farms that reported the cropping-pasture phase.

2. Methods and data

2.1. Development of the conservation agriculture appraisal index (CAAI)

The Conservation Agriculture Appraisal Index (CAAI) was developed to gauge the intensity and frequency of use of the three core CA principles: Minimum Soil Disturbance (MSD), Permanent Soil Organic Cover (PSOC) and Diversified Crop Rotation (DCR) (FAO, 2017). CAAI encompasses intermediate levels of adoption. These levels establish principle-specific thresholds (Table 1). Four 'adoption levels' are proposed: no adoption (0), minimum (1), intermediate (2) and high (3) for the core principles. Adoption levels are used to compute MSD and PSOC scores, whereas the DRC score accounts for the proportion of break

Table 1
Conservation Agriculture Appraisal Index (CAAI).

	CA Core Principles		
adoption level	Minimum Soil Disturbance (MSD)	Permanent Soil Organic Cover (PSOC)	Diversified Crop Rotation (DCR) [2, 3]
	Frequency of cultivation and type of planter. Disturbed area < 15 cm wide or < 25% of the cropped area	AND Percentage (%) of ground cover on the soil surface from crop residues, cover crops or pastures	AND Incidence (number) of break crops (including long fallows, pastures) divided by the total number of crops in the rotation in years and multiplied by a constant of 3
0	**Conventional tillage** Full tillage topsoil disturbed > 70%, >3 passes, either ploughing or harrowing (i.e. using mouldboard)	**Insufficient ground cover** No stubble retention or < 30% ground cover. Grazing, burning, residues buried or selling stubble	**Mono-cultivation (crop-only systems)** Only winter or summer cereals. No break crops, no long fallows
	OR	OR	OR
1	**Reduced tillage [8]** Reduced cultivation in a year. It involves surface soil disturbance with 3 passes in a year, which might include one shallow cultivation.	**Minimum ground cover** 30% < 50% of ground cover. Grazing is allowed and livestock is part of the farm enterprise	**Break crops of the same species** Some break crops in a short crop length rotation. Long-fallow with pillar crop. Pasture might be present.
	OR	OR	OR
2	**No-till [7]** < 30% soil disturbance in the previous 12 months. One pass using a tyne planter at sowing per cropping season.[7]	**Intermediate ground cover** Retaining 50% < 70% of ground cover. Grazing is allowed and livestock is not necessarily part of the farm enterprise.	**Some break crops and long fallows might be present** Break crops of different species with some long fallows. Pasture might be present.
	OR	OR	OR
3	**Zero-till [6, 7]** < 10% of soil disturbance in the previous 12 months. One pass using a disc planter or jab planter at sowing per cropping season. [7] None soil disturbance. [6]	**Full ground cover (Pure cropping)** Retaining ≥ 70 % of ground cover and no grazing	**More break crops including legumes and long fallows** Break crops of different species, including Inter-row sowing. Long fallows might be present. Pasture might be present.
	MSD score (0-3) [1, 6, 7, 8]	PSOC score (0-3) [1, 5]	DCR score (0-3) [1,2, 3, 4]
	CAAI score (0-9) [1]		

[1] The number in brackets depicts the minimum and maximum scores that could be obtained. Each score is a continuous variable. [2] Adoption levels to estimate DCR score is computed differently from MSD and PSOC. [3] In the DCR principle score each break crop is counted as 1, but some crops of the same species as the pillar crop can have 0.5 as it assists to break disease cycle (i.e. oats where winter cereal is the pillar crop). [4] Max DCR score is obtained only when there is no pillar crop in a rotation. In cases of cropping- pasture phases, DCR component accounts for a pasture as a break crop in the rotation length. [5] Percentage of pasture as ground cover can be quantified by PSOC. [6] Soil disturbance in long fallows and pastures with no grazing in a year qualifies for a MSD score of 3. [7] Fertilizer application or bed-reshaping are allowed provided the disturbance of the soil is no greater than at sowing. [8] Strategic cultivation would score as RT (MSD = 1) providing it happens in a period >5 years.

crops, including pastures, and long fallows in the crop rotation over years. Finally, the scores of the core principles are summed to obtain an aggregated CA score called the CAAI score. CAAI accounts for farm area and cropping season where all CA principles are consistently used to estimate CA adoption.

- Core principle 1. Minimum Soil disturbance (MSD).

MSD assesses the level of soil disturbance by farm area and cropping season. Conventional or full tillage (CT) scores 0. Reduced Tillage (RT) scores 1 and it is defined as partial disruption of the soil surface with three passes including planting (Agriculture Victoria, 2020). No-till (NT) scores 2 allowing one pass with a tyne seeder at sowing. Zero-till (ZT) receives a score of 3 with a single pass of a disc planter at sowing, (D'emden et al., 2006; Llewellyn and D'emden, 2009). Jab planters – manual tools for planting large seeds, commonly used in Africa – and hand weeding also fall under ZT (Maclaren et al., 2022). If required, fertilization or bed reshaping is allowed in NT and ZT, provided the soil disturbance is not greater than that caused by the planter at sowing. In cropping seasons where no soil disturbance of any type occurs (i.e. long-fallow) MSD scores 3 (Table 1).

Herbicide application, at any point before planting, is not counted in MSD assessments. Additionally, strategic cultivation, defined as infrequent cultivation or one-off deep tillage occurring every 4–8 years (Renton and Flower, 2015) to reduce soil compaction, control weeds (Kirkegaard et al., 2020), and/or alleviate nutrient stratification (Blanco-Canqui and Wortmann, 2020), would be treated as a form of RT and would score 1, provided it occurs only once in a period of 5 years or more.

- Core principle 2. Permanent Soil Organic Cover (PSOC).

PSOC assesses the percentage of soil organic cover, also called ground cover, from retained crop residues, depending on the crop type, including those from cover crops and pastures, on the soil surface by farm area and cropping season. Retaining surface residues, using cover crops or pastures help to protect and improve soil structure. Residue decomposition positively impacts soil properties, although factors such as rainfall, soil type and stubble management can influence the effectiveness of residue retention (Turmel et al., 2015). Adoption levels of PSOC are determined by percentage thresholds of soil ground cover. At least 30% of soil organic cover must be retained to preserve soil properties (Govaerts et al., 2007; Hobbs et al., 2008) thus attracting a score of 1 (Table 1).

Grazing from a mixed-farming or seasonal grazing by an external enterprise is allowed in PSOC. Other than burning all stubble (score zero), tactical practices such as 'windrow burning' – burning the straw from the previous crop before sowing (Walsh and Newman, 2007), or 'cool burning' – burning the retained stubble from the previous crop prior sowing (Umbers, 2017) will not impact PSOC score provided the soil remains covered and the use of these tactical strategies is infrequent. When windrow burning is routinely employed, the PSOC score would decrease by the percentage of ground cover removed. Similarly, when crops are cut for hay (e.g. frost damaged crops or to remove herbicide resistant weeds), or most stubble is reduced for commercial purposes, then PSOC score would be zero.

- Core principle 3. Diversified Crop Rotation (DCR).

Crop rotation involves growing diverse crops in sequence on the same land to avoid monoculture. DCR measures the proportion of break crops including pastures and long fallows (LF) (>9 months) over the total crop sequence. A break crop is a different species from the pillar or dominant crop(s) in the rotation (Angus et al., 2015), while long fallow skips a year of cropping (Oliver et al., 2010). To calculate the total of break crops, each break crop and long fallow in the rotation is counted as 1. Given that wheat in this study is the pillar crop, oats (*avena sativa*) are deemed a partial break crop (0.5) because it is also a winter cereal but with some break crop characteristics, including resistance to the *Ophiobolus graminis* form of take-all (Chambers and Flentje, 1967). In a typical crop rotation in Europe: rapeseed – wheat – barley, rapeseed serves as the break crop in winter cereals (wheat and barley). In a cropping-pasture phase, the pasture serves as a break crop in the rotation.

2.2. Methods for computing the CAAI score

For the first two principles the number of cropping seasons in a year (CS_T) was identified to obtain the annual proportion of each season. Then, the cropping area (CA_t) per season, where the two principles applied annually, was estimated. This computation allows to estimate partial adoption of MSD and PSOC, that is when each principle is applied in some cropping seasons and/or only on a proportion of the farm area.

- Computing core principle 1: Minimal Soil Disturbance (MSD).

First, the level of adoption (PAI_t) of MSD was identified (0,1,2,3 from Table 1, column 2) for a given farm area in each cropping season (t). Then MSD score per season is calculated from Eq. (1):

$$(MSD_T) : MSD_T = \frac{1}{CS_T}\sum_{t=0}^{n}(PAl_t)\left(\frac{CA_t \times 100}{FA_t}\right) \tag{1}$$

where PAl_t = Principle Adoption level for each cropping season within a year (t = 1……n), FA_t = Total Farm area for each cropping season (t), CA_t = Cropping Area for each cropping season (t), CS_T = Number of cropping seasons in a year.

The MSD_T score can be calculated to estimate the MSD through years Eq. (2):

$$MSD = \sum_{T=1}^{N}\frac{MSD_T}{N} \tag{2}$$

where: MSD = Minimum Soil Disturbance over time, MSD_T = Minimum Soil Disturbance for a year *(T), N* = The number of years.

- Computing core principle 2: Permanent Soil Organic Cover (PSOC).

PC is computed in a similar way to MSD. Level of adoption (PAI_t) of PSOC is identified (0,1,2,3 from Table 1, column 3) for each cropping season (t). The annual PSC_T is obtained as Eq. (3):

$$PSC_T = \frac{1}{CS_T}\sum_{t=0}^{n}(PAl_t)\left(\frac{CA_t \times 100}{FA_t}\right) \tag{3}$$

Where, PAl_t = Principle Adoption level for each cropping season within the year (t) = 1…..n, FA_t = Total Farm Area for each cropping season (t), CA_t = Cropping Area for each cropping season (t) and CS_T = Number of cropping seasons in a year.

The PSC_T score can be calculated over time to estimate the *PSOC* through years from Eq. (4):

$$PSC = \sum_{T=1}^{n}\frac{PSC_T}{N} \tag{4}$$

where: $PSOC$ = Permanent Soil Cover over time in years, $PSOC_T$ = Permanent Soil Cover for a year *(T), N* = Number of years.

- Computing core principle 3: Diversified Crop Rotation (DCR).

DCR score is determined by the incidence of break crops in the crop sequence assuming it occurs on the same farm area over a corresponding number of years. The total number of crops was calculated by summing each crop and long fallows within a sequence, starting with the pillar crop until the crop rotation resumed Eq. (5). Similarly, the number of break crops, including long fallows and pasture if any, was calculated by excluding the pillar crop and crops of the same family Eq. (6). Then the number of break crops was divided by the total number of crops in the rotation resulting in a break crop proportion Eq. (7) that was multiplied by a constant of three to generate a DCR score Eq. (8) on a 0–3 scale (Table 1).

An estimate of the total number of crops and break crops in a given crop rotation is given by Eq. (5) and Eq. (6):

$$TC = \sum_{i=1}^{n} C_i \tag{5}$$

$$BC = \sum_{i=1}^{n} B_i \tag{6}$$

where: TC is the total number of crops (C) in a suggested crop sequence over N years, and BC is the total number of break crops (B), other than winter cereals, in a crop sequence over N years. The proportion of break crops in the rotation is computed by Eq. (7):

$$BCRp = \frac{BC}{TC} \tag{7}$$

where: $BCRp$ = proportion of break crops in the rotation. Finally, The DCR score is then obtain from Eq. (8).

$$DCR = (BCRp)\,\beta \tag{8}$$

Where, $BCRp$ = proportion of the break crop for a given rotation in T years, β = scaling factor set at 3.

It was assumed that the crop rotation occurs on the whole farm area as crops are planted in different fields over years. Otherwise, the percentage of the farm area where a given crop sequence was applied was estimated. In this way, perennial crops such as alfalfa can be considered part of the rotation.

The scores of the three core principles are continuous variables ranging from 0 to 3. Aggregate CA score across the core principles is calculated. The CAAI score is the sum of the three principles, ranging from 0 to 9 (Table 1), that quantifies the annual level of CA adoption and it can be obtained from Eq. (9).

$$CAAI_T = MSD_T + PSC_T + DCR_R \tag{9}$$

Where, $CAAI_T$: Conservation Agriculture Appraisal Index for year T, MSD_T: Calculated from 1 for year T, $PSOC_T$: Calculated from 3 for year T, DCR_T: Calculated from 7 for rotation sequence R.

Therefore, CAAI indicates the level of adoption of CA over time and can be computed from Eq. (10).

$$CAAI = \sum_{T=1}^{n} \frac{CAAI_T}{N} \tag{10}$$

Four examples of the computation of CAAI by farm area and cropping season and over years are shown in Appendix B.

2.3. Full, partial and limited or no CA adoption

Full adoption implies that the three core principles are consistently applied on the whole farm over time. However, farmers often adapt in response to exogenous factors. Partial adoption occurs when CA is applied to only a proportion of the farm or during specific cropping seasons, for example summer crops may be grown under CA but not winter crops. No CA adoption is deemed to occur when none or only one or two of the CA principles are used.

In this study, a minimum level of consistent CA adoption was considered at a CAAI score of 3 (i.e. 30% of stubble retained under RT with at least one break crop included). Previous research showed that even minimum levels of CA adoption supported soil health and enhanced ecosystem services (Francaviglia et al., 2023; Govaerts et al., 2008). Because MSD and PSOC scores for each cropping season within a year are reconciled using an annual averaging procedure (Eqs. 1 and 3), the annual MSD and PSOC scores may be lower than those for individual cropping seasons within that year.

2.4. Testing the broad applicability of CAAI

2.4.1. Study regions

Four wheat growing regions were selected, two in Australia and two in Mexico, for CAAI application (Fig. 1). These regions comprised two dryland systems in Australia and two irrigated systems in Mexico. These diverse regions were chosen to test the broad applicability of CAAI. Regional differences related to biophysical conditions (agroecological-zones, irrigation/dryland production areas), economic factors (medium vs large scale farms, subsidized/non-subsidized markets), social factors (access to information, education, technical advice) and infrastructure (access to research, markets, inputs, and enabling policies).

The Australian regions included north-western New South Wales (NWNSW) and north-western Victoria (NWVIC). NWNSW encompassed areas around Narrabri, Moree and the Liverpool Plains. This region has a summer dominant rainfall and annual average rainfall varies between 480 mm and 670 mm. Winter crops largely rely on soil stored moisture from summer rainfall (Freebairn et al., 2006), which also can be used for summer crops that might require long fallows ($<$ 9 months). Average winter-time temperatures range from 13.8 °C to 14.8 °C. NWVIC comprised the Wimmera and Mallee regions. In this region rainfall is winter dominant and average temperatures throughout the winter growing season range from 10.5 °C to 11.0 °C. Summers are too dry to produce summer crops. Agriculture in both Australian regions is characterised by variable rainfall, large farms (1500–11,000 ha) and high levels of mechanization.

In Mexico, the Yaqui Valley, located in southwestern Sonora (SWSON) and southwestern Guanajuato (SWGTO) were studied. Annual rainfall in SWSON was very variable; on average 390 mm p.a. but only 73–80 mm (19%) falls during winter. Winter temperatures are mild at an average of 19.5 °C. This area accounts for 90% of Mexico's durum wheat production most of which is exported to Europe. In contrast, SWGTO has an annual summer dominant (90%) rainfall of 640–720 mm. The region has an elevation of 1700 m and winter temperatures are relatively warm (16.9 °C to 17.9 °C). This region is characterised by intensive cropping and both summer and winter crops are grown on the same land annually. Bread wheat is the dominant winter crop and maize the main summer crop. Both regions rely heavily on surface irrigation to grow winter crops.

Vertosolic soils are predominant across the four regions. The exception was the soil in some areas in the Mallee in NWVIC, where sandy or loamy sands (Calcarosols) dominate. Biophysical and farming characteristics of the regions studied can be found in Appendix C.

2.4.2. Data collection

Data were collected between May 2018 and June 2019. Mixed-methods were applied (Creswell and Plano Clark, 2010). For CAAI development, a focus group and face-to-face semi-structured interviews with farmers, agronomists and researchers were conducted in each region until no new information emerged (Guest et al., 2006). Three main questions were discussed in focus groups: What does CA mean? What components of CA are relevant to you? Challenges and benefits in the adoption of CA. For CAAI application, questionnaires and semi-structured interviews with farmers during farm visits were used. Initially, farmers identified as pioneers or early adopters and practitioners of CA were face-to-face surveyed, subsequently, late adopters and non-adopters. The data included: 32 farms (35 participants) in NWNSW, 40 farms (49 participants) in NWVIC, 11 farms (12 participants) in SWSON, and 17 farms (18 participants) in SWGTO. When

Fig. 1. Regions of study in Mexico and Australia.

necessary, clarification was sought in follow-up text messages or e-mail.

Questions0F[1] included farm size, type of farming system (cropping / mixed-farming), percentage of cropping area and/or mixed farming on the farm, type of planter used, frequency of cultivation, estimated percentage of retained stubble or any ground cover in winter and summer cropping seasons, proportion (%) of the farm area with retained stubble for each cropping season, crop sequence, and use of GPS and adoption of fixed width machinery for controlled traffic or PB instead GPS.

The questionnaire was designed with feedback of researchers with expertise in the area. While face-to-face surveys might introduce subjectivity, to minimize the bias and maintain consistency in the data collection process, the same researcher surveyed the four regions of study.

2.4.3. Data analysis

When more than one member per farm was interviewed, the answer of the decision-maker was considered for the analysis. Those enterprises with permanent livestock in the cropping system were classified as mixed farming, otherwise farms were classified as exclusively cropping. A farm classified as exclusively cropping could still allow seasonal grazing, providing there was minimal impact and at least 50% of stubble was retained (Table 4).

MSD and PSOC scores presented here were based on what farmers reported about the frequency and intensity of utilization of these core principles before and after growing wheat (during winter and summer cropping seasons), while DCR accounts for the total numbers of break crops, including long-fallows and pastures, over the length of the rotation. Then annual CAAI scores were computed.

Modified CA principles scores were generated to show reported variations in the utilization of any of the CA principles. The MDS and PSOC and modified CA principles scores were calculated in excel. R (R Core Team, 2017) was used to compute DCR and CAAI scores and modified CAAI scores, conduct data analysis and generate plots with the tidyverse package. The median was used as the key measurement of central tendency.

[1] A human ethics approval was granted (Protocol Number 2018/076) by the University of Sydney to conduct this study.

While the data presented in this study was not necessarily representative of the population in each region and could be context-specific, it still provided meaningful insights into the quantification in the adoption of CA and its principles among farmers and test and assess the potential of broad applicability of the CAAI framework.

3. Results

3.1. CAAI scores by region

Annual CAAI scores were higher in Australia compared to Mexico (Fig. 2) and the NWNSW median was higher compared to NWVIC. Most Australian farms used CA in dryland areas for summer and winter crops, while Mexican farms used CA mostly in summer crops (rainfed and irrigated) and partially in winter crops under irrigated systems (Table 4). In Mexico, SWSON had the lowest median CAAI score and a more variable range. In some farms in Mexico, annual CAAI scores were above 2 but still below 3, the point where limited or no CA adoption was observed (Fig. 2).

NWNSW and SWSON recorded the maximum CAAI score and SWGTO and NWVIC the lowest maximum score (Table 2). The lowest MSD score of 0 and PSOC scores of 0.5 were observed in both Mexican regions (Table 2). PSOC median scores were lower in Mexico compared to Australia. However, the MSD median score for SWGTO was higher than NWVIC. NWNSW had the highest DCR median score, compared to other regions (Table 2).

3.1.1. Variation in minimum soil disturbance (MSD) scores

In NWNSW, >50% of farmers used zero-till and to a lesser extent no-till (Table 3). In contrast, in NWVIC, <18% used zero-till and 60% no-till. Only 9.4% of farmers used reduced till (score 1) in NWNSW, whereas NWVIC had higher percentage (23%), partly due to permanent livestock on some farms. Cotton (*gossypium*) was grown on 78% of the farms sampled in NWNSW (data not shown). One fourth of the farms were located on the Liverpool Plains and 22% grew dryland cotton. MSD scores were not decreased by cultivation to burst pupae (data not available). However, modified MSD scores accounted for this scenario.

In SWGTO, 29.4% of farmers used zero-till, 29.4% practiced reduced till, and only 5.9% used conventional tillage throughout the year

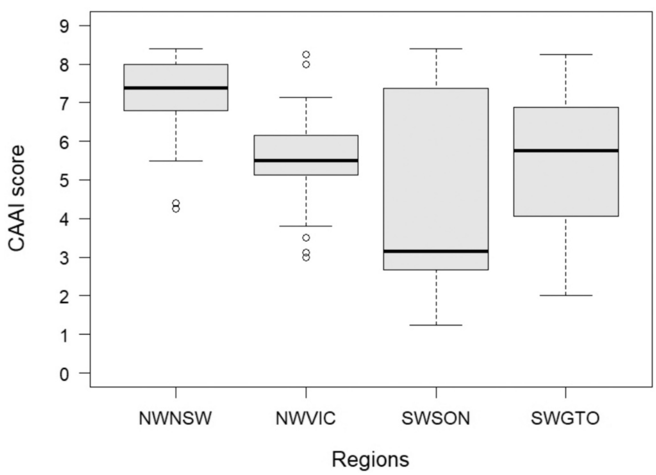

Fig. 2. Annual CAAI scores for winter (wheat grown) and summer cropping seasons across 100 farms in four cropping regions: North-western New South Wales (NWNSW), North-western Victoria (NWVIC), Southwest Sonora (SWSON) and Southwest Guanajuato (SWGTO). The median is represented by a black line in the interquartile range (25–75 percentiles) and outliers are indicated (observations > Q3 plus 1.5, and < Q1 minus 1.5). Two farms in each Mexican region score MSD =0 and three MSD <0.5 across the year for a CAAI score < 3.

Table 2
Summary of descriptive statistics for CAAI scores and its principles scores in each Region.

CAAI and CA Principles	Region	No. of Farms	Min	Median	Mean	Max	Sd
CAAI	NWNSW	32	4.5	7.4	7.2	8.4	1.6
	NWVIC	40	3.0	5.5	5.5	8.2	1.3
	SWSON	11	1.2	3.1	4.5	8.4	2.6
	SWGTO	17	2.0	5.7	5.4	8.2	12.6
Minimum Soil Disturbance (MSD)	NWNSW	32	1	3	2.5	3	0.7
	NWVIC	40	1	2	2.0	3	0.6
	SWSON	11	0	0.6	1.4	3	1.3
	SWGTO	17	0	2.5	2.1	3	0.9
Permanent Soil Organic Cover (PSOC)	NWNSW	32	1	3	2.7	3	0.7
	NWVIC	40	1	2	2.0	3	0.7
	SWSON	11	0.5	1	1.6	3	1.1
	SWGTO	17	0.5	1.5	1.6	3	0.7
Diversified Crop Rotation (DCR)	NWNSW	32	1.5	2	2	2.4	0.2
	NWVIC	40	0.8	1.5	1.5	2.2	0.3
	SWSON	11	0.8	1.5	1.6	2.4	0.5
	SWGTO	17	1.5	1.5	1.7	2.4	0.3

Min = minimum; Max = maximum, sd = standard deviation.
North-western New South Wales (NWNSW), North-western Victoria (NWVIC), Southwestern Sonora (SWSON) and Southwestern Guanajuato (SWGTO).

(Table 3). Overall, 88% of farmers zero-tilled summer crops, and only 65% zero-tilled winter crops, which typically accounted for 40% - 80% of the total crop area (data not shown). The average annual MSD score of 1.5 reflects zero-till on summer crops and full soil disturbance on winter crops. The high median score of 2.6 for SWGTO mostly reflected the high adoption of zero-till in summer crops (Table 2).

In SWSON, 36.4% of farmers used zero-till annually across the entire farm area, sowing on permanent raised-beds and reshaping if needed (Table 3). A similar percentage practiced conventional tillage annually, but occasionally tried zero-till. Zero-till is used for summer crops by 73% of farmers, but this only accounted for 10–30% of the farm area, while 55% of farms used zero-till for winter crops, however this only accounted for 20–40% of the area. On average, across the two Mexican regions, just 32% of farms reported zero-till across both winter and summer crops, and this was reflected in the median MSD score (Table 2).

3.1.2. Variation in permanent soil organic cover (PSOC) scores

NWVIC had more mixed farming interacting with the cropping area than NWNSW, and to a lesser extent SWGTO while SWSON had none (Table 4). In NWVIC, 20 farms categorized as 'cropping' allowed seasonal grazing of winter crop stubble over summer. In NWNSW twelve respondents allowed grazing of stubble only in very dry conditions and five confined livestock to restricted areas (< 5% of the farm). In SWGTO livestock accounted for <10% of the farm and most of the time animals were kept in containment areas. In these examples of 'cropping', livestock were deemed to have minimal impact on retained stubble. In most cases, grazing is allowed for a limited period.

Across all regions, only 14% of farms reported mixed farming as part of the farm enterprise. In these cases, the focus on retaining stubble for soil coverage was somewhat compromised by grazing. Overall, 86% of farmers retained between 50 and 60% of the stubble because they did not allow grazing, or at least limited grazing on an opportunistic basis or in response to drought.

In NWNSW, 75% of farms retained at least 70% of the stubble, compared to 28% in NWVIC. In Mexico, SWSON farms retained 36.4% of stubble whereas SWGTO only 5.9%. In NWVIC 20% of farmers reported windrow burning close to sowing to manage weed seed burdens, which only compromised stubble cover in the weeks prior to planting. This practice did not impact PSOC score (data not available).

Although most farmers in both Mexican regions reported retaining some stubble, occasionally cultivated soils to incorporate crop residues and chicken manure was used either after harvesting wheat, as is most common in SWSON, or before sowing to prepare raised beds. This explained the lower median PSOC score in SWSON (Table 2).

3.1.3. Variation in diversified crop rotation (DCR) scores

DCR score reflected the proportion of break crops (other than winter cereals) to the total crops in each rotation length. The choice of break crop differed in each region, as shown in the most common crop rotations in Appendix D. Most farmers aimed to grow crops in sequences guided by rotation principles but with a degree of flexibility.

NWNSW recorded the highest median DCR score with 69% of farms achieving scores ≥2 (Table 3), indicating rotation lengths ≥2 years including break crops and long fallows. Conversely, in NWVIC only 10% recorded a score ≥ 2, largely because summer crops were not sown and break crop opportunities were limited to non-cereal winter crops and long fallows in typical rotations of 3–5 years. The median score of 1.5 in NWVIC reflected that in 87.5% of the farms, break crops typically comprised 50% of the rotation.

In SWGTO and SWSON, 29% and 36.4% of farms, respectively, recorded a DCR score between 2 and 2.9. Both Mexican regions predominantly recorded DCR scores <2 with a median score of 1.5 (Table 2). In SWGTO, winter and summer crops were grown on the same land every year including corn (*zea mays*) as the main break crop or alternatively sorghum. Long fallows were absent because winter crops were irrigated, and summer crops rainfed. In SWSON, durum wheat was the main winter crop, however, chickpeas (*cicer arietinum*) and corn were increasingly grown as winter break crops. Like NWVIC, this region had very hot dry summers, therefore, summer crops were grown only on a limited farm area, and when farms had access to underground water for irrigation.

4. Discussion

The CAAI was developed to assess the intensity and the extent of CA adoption over space and time. The index provided a systematic way to estimate CA adoption by defining specific thresholds for each CA principle and quantifying their concomitant use through a scoring system. This approach captured full, partial and non-adoption of CA over farm areas and cropping seasons. Compared to earlier indices of Brown et al. (2017) and Takam Fongang et al. (2023), the CAAI accounts for the proportion of different break crops, including long fallows, in the crop

Table 3
Percentage of farms classified per level of adoption for each CA principle scores in the four regions.

Principle	Principle score	Description CA principle level	NWNSW (%)	NWVIC (%)	SWSON (%)	SWGTO (%)
Minimum Soil Disturbance (MSD)	3	• ZT	56.2	17.5	36.4	29.4
	2–2.9	• NT	34.4	60.0	0.0	35.3
	1–1.9	• RT	9.4	22.5	9.1	29.4
	0.5–0.9	• Only in some parts of the farm area and for some cropping seasons	0.0	0.0	18.2	0.0
	0–0.4	• Conventional till (mostly)	0.0	0.0	36.4	5.9
Permanent Soil Organic Cover (PSOC)	3	• ≥70%	75.0	27.5	36.4	5.9
	2–2.9	• <70% - 50%	15.6	50.0	0.0	29.4
	1–1.9	• <50% - 30%	9.4	22.5	27.3	58.8
	0.5–0.9	• <30%	0.0	0.0	36.4	5.9
	0–0.4	• None (insufficient)	0.0	0.0	0.0	0.0
Diversified Crop Rotation (DCR)	3	• Intercropping • ≥2 year crop sequence • Wheat grown only once • Diversity in break crops • Long fallows • Usually stick to the rotation	0	0.0	0.0	0.0
	2–2.9	• ≥2 year crop sequence • Wheat grown once or twice in the sequence • Some break crops • Some long fallows • More flexible rotation	68.8	10.0	36.4	29.4
	1–1.9	• ≥1 year crop sequence • Wheat grown every year with another winter cereal or a summer crop • Very rarely long fallows (if any)	31.0	87.5	45.5	70.6
	0.5–0.9	• Rarely break crops	0.0	2.5	18.5	0.0
	0–0.4	• Only wheat (monoculture)	0.0	0.0	0.0	0.0

North-western New South Wales (NWNSW), North-western Victoria (NWVIC), Southwest Sonora (SWSON) and Southwest Guanajuato (SWGTO).

Table 4
Summary of farming systems and farm characteristics between the four studied regions.

Region		Number of Farms with Mixed Farming vs Cropping			Farm characteristics			
	Production system for winter crops	Mixed- farming with grazing on cropping area	'Cropping' with seasonal grazing [a]	Cropping Only. No grazing	Average Farm Size (ha)	Average Area sown (ha)	Average Dryland (ha)	Average Irrigated (ha)
NWNSW (Aus)	Dryland	3	17 [a]	12[b]	4165.0	3400.2	3090.1	338.25[c]
NWVIC (Aus)	Dryland	9	20 [a]	11	4149.0	3794.4	3794.4	0.0
SWSON (Mex)	Irrigated	0	0	11[b]	423.8	423.8	0.0	423.8
SWGTO (Mex)	Irrigated	2	2	13	39.3	36.4	0.2	28.2

North-western New South Wales (NWNSW), North-western Victoria (NWVIC), Southwest Sonora (SWSON) and Southwest, Guanajuato (SWGTO).
[a] Grazing over summer(seasonal), or if very dry conditions and/or livestock restricted on farm area.
[b] Separate grazing enterprise from the cropping area.
[c] Irrigated area not considered for CAAI assessment.

sequence when calculating the DCR score. Additionally, thresholds for each CA principle in the CAAI were established based on outcomes from previous research ensuring a more comprehensive assessment.

4.1. Challenges in quantifying core principles and determining thresholds for consistent CA adoption

Thresholds for each principle were established to assess their level of utilization. Because the aggregation of the scores of the three core principles is indicative of the overall degree of CA adoption, consistent CA adoption could occur at various levels provided none of the scores of the principles was 0 throughout the year assessed. In this study, one farm in each of SWSON and SWGTO had CAAI scores <2, with MSD = 0, PSOC = 0.5. Additionally, three farms in SWSON had MSD and PSOC <0.5 and all of these had DCR = 1.5 except one that scored 0.75. These cases, with CAAI scores <3, were classified as limited or no CA adoption as they exhibited an inconsistent or non-adoption of the concomitant use of the three CA principles.

The challenge in establishing a threshold for CA adoption lies in the frequency and intensity with which the three core principles are applied simultaneously, either on part or the whole farm area, or for some or all cropping seasons. It should be noted that various combinations of the scores of the CA principles can result in a similar CAAI score (0–9). For instance, farmer A receives scores of DCR = 2 (avoiding monoculture), PSOC = 1 (at least 30% stubble retention) and MSD = 1 (RT), resulting in a CAAI score of 4. Meanwhile, farmer B scores DCR = 0 (monoculture), PSOC = 2 (Stubble retention >30% < 50%), MSD =2 (NT), achieving a similar CAAI score of 4. Despite having the same CAAI score, farmer B would be considered a limited or non-adopter of CA because diverse crops and/or long fallows lack in the rotation (DCR = 0).

External circumstances including access to markets or societal issues may prevent farmers from incorporating break crops. An example of this is in SWSON, where chickpea is rarely grown because the crop is stolen due to the proximity of the farm to the town. Additional factors like the availability of disease-resistant varieties could make unnecessary the inclusion of other crops for sanitation purposes. While DCR is of relevance for disease management and N conservation through rotation (Mcdaniel et al., 2014), it is documented that the first two core principles (MSD and PSOC) are key to soil conservation in the CA system (Bescansa et al., 2006). The concomitant adoption of three principles might increase soil C, mainly in the soil surface layer. Although this outcome varies depending on soil type, climatic conditions, and type of farming system (Francaviglia et al., 2023).

We believe that defining clear thresholds for the levels of utilization of the CA principles and CA adoption can provide valuable guidelines for sustainability assessments. These thresholds might help to evaluate the environmental, economic, and social impacts associated with different degrees of CA adoption. CAAI scores could serve as a useful proxy for CA adoption, benefiting policymakers, donors and farmers in their decision-making processes.

The flow-on outcomes related to each level of CA adoption, as guided by CAAI scores, and their association with soil health indicators, was not investigated in this study. However, this relationship could be further explored in future research. The following section explains the practices behind each of the CAAI scores in each region and examines potential scenarios where CAA scores are modified.

4.2. Application of the CAAI in Australian and Mexican case studies

We expanded on existing research conducted in Australia and some areas of Mexico by applying CAAI across four diverse cropping regions in both countries to determine annual CA adoption through the concurrent utilization of CA core principles, by farm area, and annual cropping season. From the summary of statistics there were differences evident in CAAI scores across regions. The absence of zero values for any of the observed annual CA core principles in Australia indicated a more consistent utilization of CA compared to Mexico (Table 2).

4.2.1. Comparison of minimum soil disturbance (MSD)

Despite similar PSOC and DCR median scores in both countries, Mexican CAAI scores were more variable mainly because MSD scores reflected greater partial implementation of CA, with strong use in summer crops sown directly into wheat stubble, but much lower adoption of CA in winter crops. The main constraints reported were the lack of access to specialized machinery for sowing wheat in heavy stubble, dealing with heavy clay soils, weed and diseases issues. This adoption and dis-adoption of CA in SWGTO has been referred to as 'periodic adoption' (Pulido and Knowler, 2020) or partial adoption (Van Den Broeck et al., 2013) like in this study.

Summer crops were mostly rainfed and sown using zero-tillage in SWGTO, or partially irrigated on raised beds from aquifers in SWSON, but only on 30% of the farm area due to limited irrigation water in aquifers. This practice was primarily driven by the need to sow summer crops immediately back into winter crop stubble, and farmers had the specialized machinery to achieve this.

Some 'strategic cultivation', referred also as infrequent cultivation, was reported for soil leveling, soil compaction and controlling weeds in all regions, similar to other studies (Conyers et al., 2019). Strategic cultivation was not captured in the MSD score (data no available). Likewise, in NWNSW cotton was part of the crop sequence and required cultivation to burst pupae, unless the new BT3 variety of cotton is planted and defoliation occurs before March 31 (Bayer Crop Science Pty Ltd, 2023). MSD scores in NWNSW did not capture the need to cultivate after harvesting cotton (data not available). However, on the assumption that growing cotton required cultivation, 84% of the farms in NWNSW had decreased MSD modified scores = 0 (Boxplot on the top right, Fig. 3).

4.2.2. Comparisons of permanent soil organic cover (PSOC)

Stubbles were either retained, grazed, or removed and sold. This was influenced by the type of farming system, commercial use, and the environment in each region. In NWNSW, the high PSOC median scores showed greater retention of stubble to maximise the storage of rain in the soil for subsequent crops, as reported earlier (Kirkegaard and Hunt, 2010). In farms operating as 'cropping only' systems and no livestock, the main motivations for retaining stubble were protection of soils, storing soil moisture, and improved soil organic matter. No farms in this study integrated cover crops in any region.

Contrastingly, the lower median PSOC scores in NWVIC and SWGTO reflected stubble grazing, feeding livestock in containment areas or stubble removal driven by economic factors specific to each region (Kirkegaard et al., 2014). Farms in NWVIC, NWNSW and SWGTO with mixed farming allowed grazing or seasonal grazing by an external enterprise (Table 4). In most farms, livestock was used as a diversification strategy to manage market and seasonal risks. Animals can contribute to increased biological activity in soils through faecal waste left in the field (Sanderson et al., 2013), and improved soil organic matter offsetting some of the negative effects of cropping (Tanaka et al., 2008). However, livestock enterprises were more vulnerable during extended drought periods.

PSOC scores did not capture the occasional cutting of crops for hay, or the stubble removed because of severe frost and/or drought, and herbicide resistant weeds. However, when oats and vetch were cut for hay on 35% of farms in NWVIC, the PSOC scores decreased by the extent of ground cover removal. If no ground cover was left, then PSOC score = 0 (Boxplot on the second row on the right, Fig. 3).

Likewise, in NWVIC windrow burning close to sowing was used 'occasionally' to manage herbicide resistant weed seeds. This did not compromise PSOC scores, as stubble was retained for almost the entire period leading up to sowing. Nonetheless, a study in Western Australia found that windrow burning decreased ground cover by 50–60% depending on the type of crop residue and time of burning (Passaris et al., 2021) and decreased SOC and N. In this study the windrow burning occurred annually. In SWGTO, at least 30% of farmers reported that stubble had a commercial value as forage. Some farmers also burnt stubble to reduce heavy stubble loads and to combat fusarium disease.

Chemical weed control on retained stubble conserved at least 20–30 mm of soil moisture (Felton et al., 1987), resulting in up to 20% higher crop yields (Lawrence et al., 1994). However, this has led to herbicide resistance (Walsh and Powles, 2014). Concerns about dependence on herbicides was reported by 70% of Australian farmers, and at least 50% of farmers in SWSON (data not shown). In Mexico, mechanical weed control was more common for winter crops, and this impacted MSD.

4.2.3. Comparison of diversified crop rotations (DCR)

DCR scores captured the frequency and diversity of crops (other than the dominant species wheat or barley) in the crop sequence. Given the range of observed DCR scores accounted for the proportion of break crops in the sequence, the maximum possible DCR score was 2.4 which indicates that 80% of the rotation included break crops and/or long fallow.

Several factors determined the crops grown in each region; i.e. markets, access to water, specialized machinery, soil types and opportunism driven by climate, and weed and disease control. Both NWNSW and SWGTO were characterised by summer dominant rainfall and similar vertosolic soils that hold larger amounts of moisture. The high median DCR score in NWNSW was a function of longer rotations and more break crops, including long fallows, compared to other regions. A review of published reports of the effect of break crops on wheat grain production showed that wheat yield was higher after a break crop and/or long fallow (Angus et al., 2015). In SWGTO, DCR reflected the opportunity to grow both winter (irrigated) and summer crops (rainfed) on

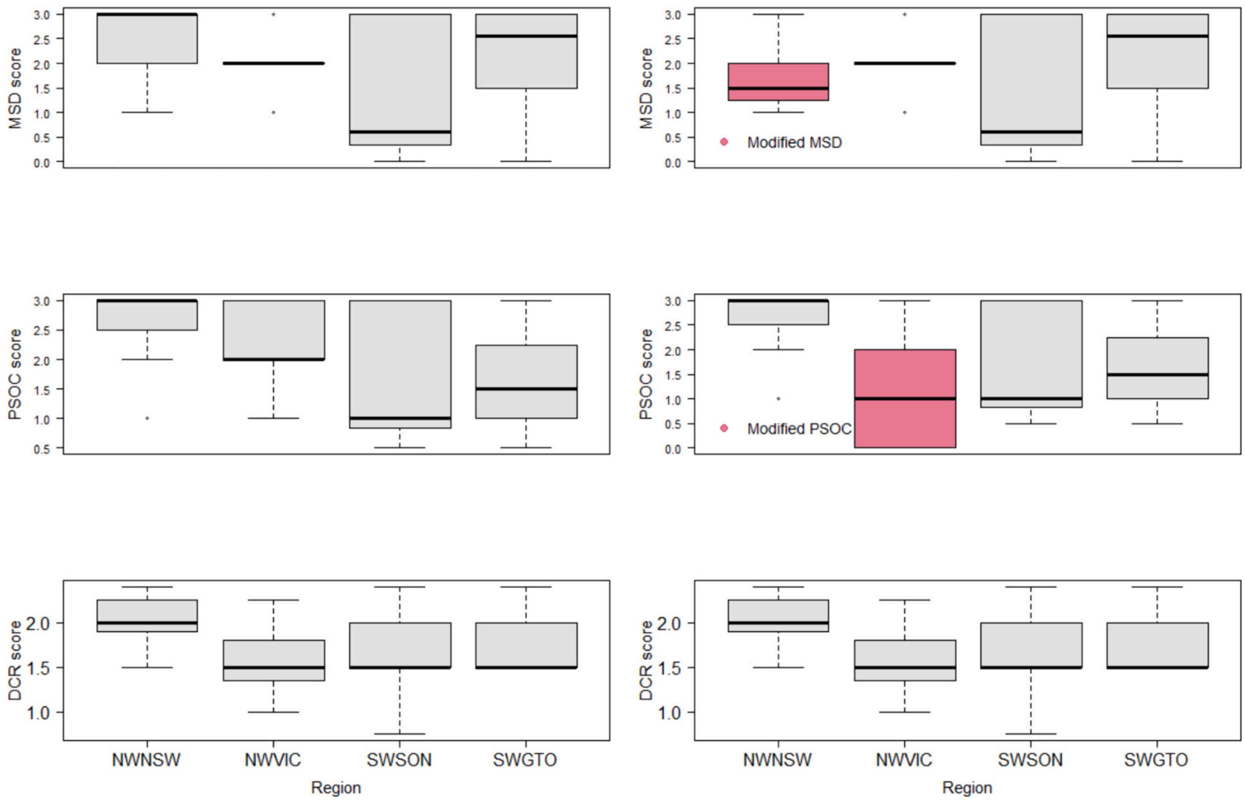

Fig. 3. Box plots comparing observed CA principles scores with modified MSD scores (growing cotton), modified PSOC scores (growing oats/vetch for hay). Median is used as the key statistics.

the same land with absence of long fallows and a variety of other crops.

In NWNSW, cotton was widely grown as a profitable crop, usually after long-fallow to ensure sufficient soil water. However, this choice likely precluded the possibility of planting chickpeas in the next winter season, whereas there was a likelihood of sowing chickpeas after sorghum in a 'double cropping' scenario.

NWVIC and SWSON summer crops are rarely grown due to high temperatures and limited availability of water. In NWVIC, canola was sown as a cash break crop, and usually included in four-year rotations. Canola was generally grown after a grain legume, and sometimes after a twelve month fallow out of cereals. Oats and vetch were also profitable for hay production. Vetch as a legume scored a DCR = 1, whereas oaten hay received a lower score if most of the crop residue was removed. Likewise, in SWSON, the higher price of corn and chickpea in 2018 and 2019 made both crops more profitable than durum wheat, the pillar crop. Although corn is a summer crop in the region, it is sown between November-mid January and therefore competes with wheat as an irrigated crop.

4.3. Future application of CAAI

CAAI can be used as a diagnostic research tool to assess the adoption of CA at the farm level and identify both full and partial CA adoption by farm area and cropping season. Moreover, it can be used effectively in longitudinal studies that encompass different cropping seasons to generate long-term information for use by research agencies and government institutions, to monitor outcomes associated with varying levels of CAAI scores and compare trends within and between regions.

While CAAI could be used as a standardized methodology for assessing the adoption of CA principles (and hence CA), we also acknowledge that the methodology used in this farm-based study relied on resource intensive collection of qualitative data, which allowed the development of CAAI. Future applications of CAAI could include technological tools such as satellite imagery or remote sensing using Landsat or Sentinel 2 A to rapidly and accurately capture the percentage of ground cover and crops grown on the same land each season (Stonehouse, 1997; Tariq et al., 2023). Sensors mounted on the planters could also provide information on the level of soil disturbance. Using time-efficient technologies and automating the calculation of the index will allow research agencies and governments institutions use CAAI more effectively for scaling up. However, the infrastructural requirement for consistent data collection using CAAI framework would demand technological and human investment.

Most importantly, Palm et al. (2014) suggested that unravelling the effects of the CA principles along with their interactions with soil type and climate across various sites, is needed to understand the ecosystem service outcomes and crop productivity resulting from the combine effect of the CA practices. This understanding is crucial for assessing site-specific CA suitability and sustainability. In a review by Teixeira et al. (2022) ecosystem service indicators were identified and used to quantify the impact of diversification of coffee production in agroforestry and its sustainability. Therefore, CAAI can be used as a research tool to further investigate the varying levels of CA adoption (CAAI scores) and the flow-on outcomes to ecosystems service indicators such as: biophysical and chemical soil parameters, biodiversity, nutrient cycling, water use efficiency, farm input use and socio-economic factors to assess the impact of varying degrees of CA adoption on the sustainability of cropping systems.

Controlled-traffic farming and permanent beds are important components of some CA farming systems because they help reduce compaction, improve soil quality and soil aggregate distribution (Chamen, 2006; Verhulst et al., 2011). However, they were not considered in the development of CAAI. Controlled-traffic farming is typically implemented by large scale farms to improve the efficiency of field operations using GPS (Vermeulen et al., 2010), whereas permanent beds are commonly used in irrigated systems on small and medium scale farms, often in developing countries (Sayre and Hobbs, 2004). In future modifications of the CAAI, both practices could be further investigated to be included either as a subcategory of the MSD principle, potentially giving it more weight, or as an additional principle with minimal weight.

Moreover, the CAAI framework can be applied to assess the adoption of CA principles on farms with cropping-pasture phases, based on the level of soil disturbance and the percentage of ground cover each year during both the cropping and the pasture phases. However, further investigation is required to determine the impact of grazing on soil properties in the absence of tillage in pastures to accurately reflect this in the MSD score, and to provide guidance on sustainable grazing practices through optimised stocking rates and grazing periods.

5. Conclusions

CAAI was introduced to address some shortcomings of previous indices. CAAI provides a standardized methodology for estimating CA adoption by establishing thresholds for each CA core principle that determine levels of CA adoption. The CAAI scores (0–9) captured full, partial and no CA adoption across the farm area and throughout each cropping season in heterogenous environments in Australia and Mexico. While a high CAAI score indicates a higher level of CA adoption, it does not necessarily equate to an achievable score within each region. Instead, each CAAI score is relative to the potential maximum CA score possible in each region, recognizing that there are constraints to achieving the highest scores. A comprehensive assessment of a given CAAI score requires an examination of the context in which it is generated, considering the environmental, economic and social factors specific to the region.

Further research is required to apply CAAI in different regions using more time-efficient technologies. Additionally, the extent to which CTF, including PB, is relevant to CAAI, as well as the application of CAAI in cropping-pasture phases, should be investigated. Finally, the relationship between the flow-on outcomes of each CAAI score, indicative of a level of CA adoption, and the underlying soil quality parameters that contribute to a sustainable cropping system needs to be explored.

CRediT authorship contribution statement

Laura I. Ruiz-Espinosa: Writing – original draft, Visualization, Methodology, Funding acquisition, Data curation, Conceptualization. **Nele Verhulst:** Writing – review & editing, Methodology, Conceptualization. **Floris van Ogtrop:** Writing – review & editing, Supervision, Formal analysis. **Rebecca Cross:** Writing – review & editing, Methodology, Conceptualization. **Bram Govaerts:** Writing – review & editing, Resources. **Harm van Rees:** Writing – review & editing. **Richard Trethowan:** Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendices

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