Response to comments made by **Anonymous Referee #1** (*Authors answers in Italic)*

It should be acknowledged that the line numbers pointing to locations of revisions in the manuscript may not reflect the location in the final revised manuscript. The up-to-now revision is available upon referee's request by Email: daniel@agri.gov.il

1) I applaud the author for attempting to explain some of the mystery's surrounding water flow in cracking clay soils and in the groundwater systems under them. I would encourage you to continue with this but as yet you have not succeeded in mounting convincing arguments around several key points, and as such the paper requires major revision before it should be published. Some of these weaknesses are:

1) We thank the referee for his/her efforts made on this elaborated and constructive review (and for his/her applaud). We are sure that the comments improved the manuscript.

2) You have not provided convincing evidence that the high deep drainage rates see in many studies on Vertisols, especially when irrigated, require preferential flow in cracks, and that it can't be explained by matrix flow.

2) This review does not claim that relatively high deep-drainage rates in cultivated vertisols (moreover irrigated) require preferential flow in cracks. On the contrary, Section 4 describes the high fluxes that were reported to develop in the matrix of cultivated vertisols and their consequences on salt flushing and salinization.

3) You have not considered the possibility of either palaeo-recharge or river recharge being the source of the low salinity groundwater.

3) This review is on soil-aquifer phenomenon affecting groundwater under vertisols, hence river-bed, paleo, or mountain-front recharge that may cause a situation of relatively fresh aquifer under a saline vadose zone, are not something that should be elaborated upon here. The soil aquifer phenomenon of interest, also in such cases, is the salinization of the aquifer after intensive cultivation begins on land surface, is elaborated upon in section 4. Nevertheless we understand the referee's concern of the text at the end of section 3 and beginning of section 4 being a little biased towards the crack related phenomenon and included other ("non vertisolic") processes that have influence on some aquifers under vertisols (lines 306-316 in the revised text).

4) You should explore the differences in the implications of cracks in dryland/rainfed and irrigated/ponded ('free water') situations. Is water flow in cracks exclusively due to "free water" (e.g. furrow irrigation, ponded water)? How much contribution does the rare instance of rainfall derived runoff occurring when cracks are present?

4) We thank the referee for this suggestion. We did acknowledge some different behavior of deep drainage under different surface-wetting conditions and thanks to this comment did a few changes to highlight the differences (e.g .lines 109 – 110 in the revised text) acknowledging furrow irrigation in Ringrose-Voase and Nadelko (2013) versus spray irrigation in Greve et al., 2010 in lysimeter experiments. Field scale studies that deal with irrigation and preferential flow were discussed in a long paragraph in the original manuscript (P. 5 line 21 – P.6 line 6).

The effect of cracks on water and vapor fluxes is much smaller in cultivated land than it is in native-vegetation land yet we mention many studies that reported preferential flow also under cultivated land in section 2.1.
In non-cultivated verstisols it is not rare that rainfall runoff percolate through cracks at the beginning of the rainy season and after dry weeks within the wet season (see P. lines 7 – 15). Further more some deep cracks do not seal completely (section 2.1). Preferential flow may occur also in cracks between rows in orchards and in non-tiled crop fields in vertisols.
A comparison between the strength of deep drainage in rainfed cropping versus irrigated cropping, was added in section 4 (lines 321-329)

5) You have not provided convincing evidence that evaporation from cracks has a large contribution to total water loss compared with transpiration. The hot/cold model does not really help as on hot days the temperatures are usually the other way around.

5) It is obvious that in wet conditions and deep rooted vegetation transpiration is the dominant mechanism that dries up the deep vadose zone, and that will be right for any type of soil. Nevertheless, this article is about cracking clays so in comparison to other soils there are cracks that have additional deep drying capacity, making the phenomenon of dry and saline deep vadose zone more significant under vertsols. We elaborated on that in section 4 of the review.
Evaporation through cracks occur at nights when surface temperature falls and warmer air is found deep in the crack while cooler air is on top of it near ground surface, causing instability.

6) You have under played role of the deep roots in native vegetation and of transpiration as main cause of cracks. Also there should be a lack of cracks below the root zone. One approach is to point out where these weaknesses are and make the need for further work on them a feature of the paper.

6) - We declare in the introduction that this review does not cover cracking dynamics.
- In Mediterranean climate some areas are covered with winter vegetation which is completely dry in mid-summer and deep soil cracks are wide open at times when there is no root activity.

7) Abstract A reasonable summation of the paper.
Good

8) General/Introduction "Vertisols usually form in lowlands (Yaalon, 1997)" Minor point butthey also occur in upland basalt areas where they usually recharge productive aquifersand rolling lands formed on sedimentary rocks with poor, saline aquifers, at least in Australia.

8) The sentence sais "usually" and for this paper the triplet of vertisol, agriculture, and groundwater is more relevant in lowlands.

9) You could also explain that the evidence for preferential flow is mixed. Many studies of deep drainage/recharge do not explain the mechanism involved (your first section, 2.1) whereas tracer and some lysimeter studies (second section, 2.2) do define the mechanism/proportions involved. Also preferential flow seems to be conditional (e.g. deep rooted vegetation different to cropping, moisture content effects; more likely to occur under furrow irrigation than rainfall).

9) The review is about Soil-Aquifer Phenomena Affecting Groundwater under Vertisols, and highlights the special phenomenon related to cracking clays. Section 2.1 is titled: Preferential flow of water in vertisols—evidence from the lysimeter to aquifer scale, it is not a discussion on deep drainage/recharge. Nevertheless, we agree with the referee that some of the field scale observations that reported deep drainage losses in cracking clays may be caused by crack or matrix flows therefore we acknowledged that where its relevant in the revised text (line 133).

10) 2.1. Preferential flow of water in vertisols
Lines 127-129. Note that these references
do report high rates of deep drainage, but they do not differentiate between matrix and preferential flow. To keep this point clear, you should review the rates of drainage observed without attributing it to preferential flow, and then separately review those studies which have evidence of the flow pathway, or proportions, responsible for the drainage. High deep drainage rate does not necessarily require preferential flow – matrix flow is sufficient. I doubt that Raine and Bakker, 1996; Dalton et al., 2001; Moss et al., 2001; Smith et al., 2005 would have been able to separate the type of flow either.

10) . A clarification acknowledging that deep drainage in these studies may include preferential and matrix flows was introduced in the revised text (line 133)

11) In a variable tension lysimeter (like that of Ringrose-Voase and Nadelko (2013)), Silburn et al. (2013) found the proportion of preferential flow was small compared to total drainage & matrix flow. The soil in this case was not cracked and had been _field capacity for a considerable period, indicating that flow through closed cracks is limited. Rapid flow still occurred but this was attributed to high suction gradients as the wetting front advanced. This does not rule out preferential flow at other moisture contents. See section 'Understanding flow processes in clay soilsâˇAˇ Tvariable tension lysimeters and tensiometry' in Silburn et al. (2013). "Deep drainage measured at 1m depth was dominated by matrix flow, with only 10% of drainage attributed to preferential flow (note that the soil was never dry enough to crack); that is, 90% of drainage was explained by Darcy flow." You could mention this at line 116.

11) Not sure that preferential flow is lesser than matrix drainage at the Ringrose-Voase and Nadelko (2013) case who acknowledge "Bypass drainage appears to account for most of the drainage during the measurement period". Neverhelless thank you for pointing to another lysimeter measurement case were matrix flow certainly dominates. We added this observation to the revised text (line 112-117)

12) Your observation on line 122 is compatible with the lysimeter measurements of Foley/ Silburn; clay soils develop large suction gradients and flow rates.

12) Although gradients are high across the wetting front in the matrix the hydraulic conductivity of the clay is low, and fronts will advance at relatively smaller velocities (m/day, weeks, month). Baram et al., 2012 report wetting-fronts velocities of a few meters per hour in non-cultivated cracking clay which cannot be explained with matrix flow.

13) Line 138: "sandier soils (Alfisols)" .. these soils are highly likely to be hard setting,

lacking in aggregation and poorly structured : : : such soils also occur in Australia. They would be expected to have high runoff. For example, Littleboy et al. (1999) Aust. J. Soil Res. calibrated a runoff curve number of 94 for cultivated Alfisol in India, compared to a CNbare of 74 for Vertosols at a number of sites. So calling them sandier is not really correct; they have enough fines to fill the pores between the coarse particles. It is the large plant available water capacity and the good structure and aggregation that explain the lower runoff from the Vertisols.

13) We cite Pathak et al., 2013 work from India in this line. At that work the vertisols had 12-22% by weight in the sand interval of particle size (0.05 – 2mm) whereas the alfisols samples had 42 – 75% of the particles in the sand interval so they are sandier.
Generally vertisols will contain 30% or more clay by definition whereas in alfisols will usually have a clay fraction of less than 30%.

14) Lines 145-147. Dafny and Silburn (2014) do mention flow in preferential pathways as an additional mechanism to matrix flow and that diffuse recharge is now included in groundwater models. However, they do not say “modelers had to include a diffuse (areal) recharge flux through soil cracks.” The part about soil cracks in incorrect – it might be true but Dafny & Silburn didn’t say it.

15) Thank you for the comment, we agree with the referee the citation is a little biased towards the purpose of this section: Preferential flow of water in vertisols—evidence from the lysimeter to aquifer scale. The reason for the somehow biased citation is the sentence from Dafny and Silburn (2014): “ Following the growing evidence of the feasibility of percolation through cracking clays, several recent studies have included a component of diffuse recharge in their assumptions or models …” the term “ percolation through cracking clays” lead to “recharge flux through soil cracks”. The paragraph was changed to better reflect Dafny and Silburn (2014) ideas of “diffuse recharge” in the Condamine River Alluvial Aquifer (lines 156-160)

16) Lines 148-150. My memory of Kurtzman and Scanlon (2011) is that they attributed the existence of fresh groundwater to recharge flow through preferential paths that bypassed the saline vadose-zone matrix under pre-agricultural deep rooted native vegetation but that this process ceased once agriculture started, and then recharge through the matrix caused salt export to groundwater and increasing salinities. Adding the latter part of the story gives a richer picture I think.

16) Salinization of groundwater after land use change under some vertisols (including the case studied by Kurtzman and Scanlon 2011) is described in section 4, and shouldn’t be introduced in section 2.1.

17) 2.2. Preferential transport in vertisols
This section makes a stronger case for your story
because the studies directly or indirectly reveal the mechanism involved. The Hardie case is interesting: it reinforces that “free water” is needed for flow to occur through preferential flow paths – in his case by saturation occurring in the sandy A horizon (I assume). Thus preferential flow should be more likely with e.g. furrow irrigation, dairy ponds etc, than under rainfall.
You might find the paper by Prendergast (1995) of interest,
although it might go against you case for flow in cracks somewhat. “Prendergast (1995) has shown that bypass flow can have the same Cl concentrations as the soil

matrix pore water” (Silburn et al. 2013). Prendergast JB (1995)
. Soil Science Society of America Journal 59,
1531–1539. doi:10.2136/sssaj1995.03615995005900060004x

17) Deep drainage through soil cracks is a more significant phenomenon in non-cultivated vertisols, where cracks are well developed. It certainly requires substantial rain events that produces runoff. Evidence that soil cracks do not seal completely (Baram et al., 2012) make this phenomenon possible well into the rainy season. In cultivated land significant preferential flow may occur at the edge of rice paddies or in paddies between seasons; in drip irrigation orchards where cracks may develop at the center of the rows between (parallel) drip (tree) lines (the same occurs in some crop fields); in furrow-irrigation as reported by Ringrose-Voase and Nadelko (2013) and others. More uniform distribution of irrigation water (e.g. frequent sprinkling) and tillage are less favorable for desiccation cracks development and deep preferential drainage through cracks.
Significant deep percolation of storm water through cracks bypassing the matrix will result in relatively fresh-water deep-drainage. Saline bypass flow is possible in smaller deep drainage events. Salt deposits on the dry crack walls as a result of the DCIS mechanism described in the paper and if the preferential by pass flow is small dissolution of the salt deposits may cause relatively high salinity in the bypass flow similar to matrix flow. Prendergast 1995 shows that using chloride concentrations at 2 depths below the root zone to estimate bypass fluxes assuming the bypass salinity is negligible does not fit tracer fast arrival (bypass), hence the assumption of negligible salinity in the bypass flow should be rejected. The analysis there is based on soil samples and there is no direct observation of bypass salinity versus matrix flow salinity, therefore we do not think it gives a strong contribution and prefer not to mention it.

18) 2.3. Development of flow and transport models in cracking clays
Line 207. Form needs to be from.

18) Corrected, thanks.

19) Line 226-227. “Hendriks et al. (1999) used a code
named” this sentence does not seem to make sense.

19) Clarified line 231 - 232

20) Line 236. What do these models tell us about the proportion of preferential flow and the conditions where this proportion is larger or smaller? The paper would be improved if the outcomes of using these models are included.

20) Section 2.3 describes the development of flow and transport models in cracking clays from the general mobile-immobile, to the fracture oriented models and more recently the full dual permeability with cracking dynamics. In other places in the review we mention works where models contributed to understand mechanism (e.g. Sun and Cornish, 2005).
The aim of this work is to highlight soil aquifer phenomenon in vertisols. Compilation of works reporting the proportion of matrix and crack deep-drainage in different conditions is not a main theme of the review, nevertheless some works that provide such proportions are discussed in section 2.1.

21) Soil cracks as deep evaporators and unsaturated-zone salinity Why is this section 3

and not 2.4?

21) Section 2 is about preferential flow and transport of water and solutes in cracks and section 3 is about evaporation through cracks and unsaturated zone salinity under vertisols.

22) 247-248. “water uptake by roots was limited to the upper 1 m of the soil profile” – this statement is not justified by the data given in the publications cited: Native vegetation including trees: Silburn et al. 2009 found water use by native vegetation (& pasture, weeds and crops; unpublished data) to the depth of sampling _1.8 m. Radford et al., 2009 found dry soil under native vegetation to 3 m at several sites; other sites presumable had received more rainfall. Silburn et al., 2011 found dryer soil to 4+ m at three out of four Cl sites under native vegetation. The additional 8m deep core had tree water use /dryer soil to at least 3 m and somewhat drier soil to 7-8m. These types of native vegetation have lived in soil with high sub-soil salinity for 1000’s of years. The extra osmotic potential created by these salinities is only a few bars (from memory). (Many crops use water to nearly 2 m in many Vertosols, pastures can be to 2.5m; 1 m for native vegetation is unlikely).

22) The text was modified to be clearer that the root depth of 1 m was not the case in the Australian case studies that reported saline deep vadose zones (lines 256-260).
Deep roots evaporate water from deep in the unsaturated zone profile in many type of soils. The main difference between cracking clays and other soils are the cracks. Therefore the hydraulic mechanisms that are facilitated by the cracks are highlighted in this review. Other mechanism like matrix percolation in high water contents and water up take by deep roots occur in vertisols as well as in other soils therefore they are not the focus of the review.

23) 249-250. This is not logical. The salinity profiles can easily be explained by matrix infiltration refilling the soil water to 2-4m (i.e. root zone) and subsequent removal of water by transpiration. The small rates of deep drainage (e.g. 1 mm/yr) below the root zone contain high salinities and have salinised the unsaturated zone over 1000’s of year. Raats (1974) simulated this scenario. Large amounts of rainwater/ runoff entering cracks would have been more likely to created low salinities in deep layer. Raats PAC (1974) Steady flows of water and salt in uniform soil profiles with plant roots. Soil Science Society of America Proceedings 38, 717–722. doi:10.2136/sssaj1974.03615995003800050012x

23) We have no argument with the referee that many unsaturated zones under native lands in semi-arid areas are relatively dry, immobile and saline due to 1000s of years of transpiration of deep rooted vegetation. What we are saying that in cracking clays even if no deep roots are found (e.g. dry hot season in places with no perennials where the winter shrubs are totally dry) deep cracks contribute to the same mechanism of drying the deep vadose zone.

24) Sun and Cornish (2005) – they probably needed to do this to explain deep water use by native vegetation (believed to be many meters, Kath et al 2014). “groundwater depth thresholds identified in the range from 12.1 m to 22.6 m for E. camaldulensis and 12.6 m to 26.6 m for E. populnea beyond which canopy condition declined abruptly” i.e. tree decline occurred (only) when groundwater was pumped down to these thresholds; Kath et al (2014) - Kath et al (2014) Groundwater decline and tree change in floodplain landscapes: Identifying non-linear threshold responses in canopy condition. Global

Ecology and Conservation 2 (2014) 148–1.

24) Trees with roots in groundwater may be a source of deep evaporation in dry periods. Another type of evaporation from deep soils that is characteristics of cracking clays, in dry period are deep soil cracks. Text was modified to show both sources of deep evaporation under vertisols (lines 261-267).

25) I don't think you have made a convincing case to this section. You could equally explore the proposition that cracks form where the soil is most dry and further drying is at low rates. The description of DCIS does not at much to the discussion. Also you don't cite actual studies of evaporation from cracks – I assume there are some?

25) We do not agree with this comment. Baram et al., 2013 provides calculations of deep evaporation near a dairy farm waste lagoon in an area with hardly any vegetation and many deep crack, where chloride mass balance (and mechanistic flow models) fitted to observation showed that 85% of the infiltrating water evaporate. The potential of the convective evaporation process suggested by DCIS is very high – of course the moisture flowing to the crack walls is the limitation for actual evaporation.
We cited other works that worked on evaporation of the same mechanism in fractured rock which all show the high potential for evaporation through cracks. More indirect (large scale) and laboratory and field works that support the evaporation through soil cracks were added to the revised text (text modified 265-271, 280-291).

26) Line 265. "(Fig. 2). Under non-cultivated soils" – something wrong here.

26) *We do not understand this comment (there is no such text in the manuscript)*

27) Line 266 In many semiarid regions, : : : add "with native, perennial vegetation". Note it is mainly the large water use compared to rainfall and the large water storage capacity of vertisols that limits deep drainage; the low hydraulic conductivity not really the issue (as seen once they are converted to cropping or irrigation.

27) The water uptake by vegetation comes just a little down the sentence.
Dry and saline deep vertisols are found also in areas with very limited perennial vegetation. At high water contents the low hydraulic conductivity of clay (relative to lighter soils) plays a role in the relatively small deep matrix percolation. The retention capacity of clay was added (line 280).

28) Lines 270-278. Yes I can see the logic of this (as per Kurtzman et al). But equally, why are most non alluvial and some alluvial areas of vertisols in Australia underlain by many meter of saline unsaturated zone and groundwater of salinities of 20,000-50,000 uS/cm?? Classic examples of the situation you are describing are the Condamine (Dafny & Silburn 2014), Lockyer and Callide alluvial groundwater systems; in each case recharge from the river is the mechanism used to explain the fresh recharge. In contrast, many of the Vertosol sites of Tolmie et al, Radford et al, Silburn et al 2009, 2011 have the situation you describe in the soil profile but lack fresh groundwater (& a river!). What is the difference between these two cases other than having a river?

28) *See answer to comment number 3*

29) Impact of cultivation on flushing of the unsaturated zone and aquifer salinization Line 284 “ii) deep soil evaporators”. Again, there is strong evidence for 1) deeper native veg roots, 2) large transpiration removing soil water, but relatively little evidence for deep losses by evaporation. Without roots removing deep soil water there will be no cracks.

29) See answers to comments number 22-25

30) Lines 287-288. Yes to that part.
Good

31) Lines 308-310. I thought part of your argument (Kurtzman et al) was that conversion to cultivation removed the deep water use and cracking, increased the deep drainage rate and converted more of the drainage to matrix flow, thus the additional salt flushing/leaching. Why go back to preferential flow & deep soil evaporation here – weakens you argument?

31)We thank the referee very much for this comment, the original organization of the sentence within this paragraph was not very clear. The sentence was rewritten to clear that the salinization of an aquifer due to cultivation may be more pronounced in vertisols rather than only the salt flushing phenomenon described before, which is a result of matrix flow (345-349).

32) Lines 314-316. Did the loamy-sand soils have lower salinities that the vertisols.

32) *Concentrations of chloride*
Under loamy sands: 1933 – mostly 50-100 mg/l; 2007 – mostly 100-250 mg/l
Under vertisols: 1933 – mostly 100-300 mg/l; 2007 – mostly 600 – 2000 mg/l

33) Relatively little nitrate contamination in aquifers under Vertisols
Line 350: “loams whereas under cultivated vertisols seldom sporadic wells produce water” : : : missing a word

33) a coma was added before whereas

34) Lines 356-360. Silburn et al. (2013) indicate the modern deep drainage and any solutes are still migrating down through the unsaturated zone in these clayey alluvial systems, and that they were very dry to many meters under native veg (water use/root zone). Recent soil sampling indicates large concentrations of nitrate in the deeper subsoil (to 1.6m) under irrigated cotton. Stratification of new water on top of old water would also make detection difficult in normally constructed wells.

34)These lines describe groundwater phenomenon rather than unsaturated zone observations. The reasons for the lack of nitrate contaminations in groundwater under vertisols are discussed in the following paragraphs. As suggested by the referee: A paragraph in which the slow unsaturated flow is mentioned as the reason for little groundwater contamination was added (thou not the case for the Israeli Coastal Aquifer; lines 400-406).

35) Line 368 “DOC in the lighter soils was higher than 15 mg/kg dry soil, only in the top 1

meter in the" move the comma to after "top 1 meter"

35) *Corrected as suggested (line 416).*

36) Line 379: need pH on <5.5 but more likely less to have anion exchange, but most Vertisols are neutral to alkaline throughout.

36) We thank the referee for this constructive comment. A sentence acknowledging pH as a limiting factor for nitrate adsorption was added (lines 434-436)

37) The Burdekin irrigation area is a large aquifer in Northern coastal Australia. It has two main soil; heavy clays and well drained lighter textured soil ("the delta"). Rising water levels have been occurring for a long time in both. A large excess of nitrogen fertiliser has long been used on the main crop, sugar cane. High nitrates have long been a feature of the aquifer under the lighter textured soil. However, there is now evidence of rising nitrate concentrations in the aquifer under the clay soils as well. To me this is saying the deep drainage and nitrates was delayed in the unsaturated zone and have started arriving at the water table.

38) Good to know the phenomenon of rising nitrate concentration under the lighter soil is observed in other aquifers (any publication available?). Was there salinization under the clays? Can the rising water tables under the clays be explained without accounting for recharge from the irrigated land above? If so, maybe the lack of nitrate-concentration rise under the clay should be explained by the mechanism suggested in this paper.
In irrigated areas above exploited aquifers water-level rise comes usually after decline of pumping due to salinization of the aquifer.

39) Overview The fact that cracks are formed mainly by plants extracting water, and that deep cracks can only form if plants extracted water at some time in the past, is not mentioned. Soil evaporation alone is only capable of shallow fine cracking (self-mulching) if starting form an uncracked condition.

39) See answer to comment # 6

40) References Silburn, M. and Montgomery, J.: Deep drainage under irrigated cotton in Australia: a review, Cotton Consultants Association Meeting, Dalby, Queensland, 21–22 June 2001, 2001. Should be replaced with one of these: Silburn DM and Montgomery J (2004). Deep drainage under irrigated cotton in Australia – A review. WATERpak a guide for irrigation management in cotton. Section 2.4. pp. 29-40. (Cotton Research and Development Corporation/Australian Cotton Cooperative Research Centre, Narrabri). Silburn DM, Montgomery J, McGarry D, Gunawardena T, Foley J, Ringrose-Voase A, Nadelko A (2013). Deep Drainage Under Irrigated Cotton in Australia – A Review. WATERpak Chapter 1.5. (Cotton Research and Development Corporation, Narrabri, Australia). pp. 40-58. 2013 is an update of the 2004 paper, which started as the CCA (unpublished) paper.

40) We assume the referee is one of the authors of this publication, and changed the citation as requested to the 2004 version (lines 809-812).

Response to comments made by **Anonymous Referee #2** (*Authors answers follow referee comments)*

1) This paper reviews published research related to several aspects of water and solute transport to aquifers overlain by vertisols. Four main sections cover the topics of preferential flow through shrinkage cracks, processes of salinity enhancement at depth in vertisols, effects of cultivation on the flushing of salts to the aquifer under vertisols, and properties of vertisols that inhibit the transport of nitrate to the aquifer. This is a broad range of subject matter, important for agriculture, contaminant hydrology, and understanding of unsaturated zone processes. The literature selected for inclusion is pertinent to these subjects, and the organization is appropriate. The reasoning is sound, and the material is presented in an easy-to-understand way. However, the manuscript needs further development and revision before publication in HESS.

1) We thank the referee for the good and positive summary of the study.

2) The paper does not follow a typical pattern of scientific journal articles. As a review, it is not very comprehensive. The articles cited represent a smaller portion of the relevant literature, and their contributions are not presented in as much detail, as normally expected for a review article. For example, a quick literature search on one of the subtopics, related to salinization, turned up at least three works that were not included but possibly worthwhile (Adams and Hanks, 1964; Rhoades et al., 1997; Ben-Hur and Assouline, 2002).

3) We agree with the referee the paper reads in some ways more as a critical review than as a comprehensive review and we prefer not to define it as either in the title. As the reviewer acknowledged in comment # 1" the material is presented in an easy-to-understand way" *which is the rational that led to the structure and also dictated a not-to long manuscript.*
The 4 subjects structure lead in some cases to a situation in which a citation of a work reflects the contribution of that work to the section's subject and significant parts of that work will not be mentioned. This is perhaps what gives the referee the feeling that some citations' contributions are not presented in as much detail, as normally expected for a review article. *For example Hardie et al., 2011 are cited for their observation that more than 94% of matrix in the vertic horizon was bypassed due to preferential flow and transport in the dye experiment rather than the comparison preferential flow at wet versus dry conditions which is in the focus of that study. This is done, in section 2.2 to bring a relatively high number of works that report the bypass flow in tracer experiments in a relatively short writing that builds up the referees acknowledgment: "*The reasoning is sound, and the material is presented in an easy-to-understand way". *Going into a more detailed report of every reference would have weakened the review overlook which is in*

this case: Many evidence of bypass transport in vertisols including tracer tests, and observation of different types of contaminant transport.
We thank the referee for pointing out more relevant works, and we are sure there are many more. The citations are biased towards works from the hydrological arena and literature because it is a study in hydrology. Whereas relevant agronomical, land-conservation studies, like those suggested by the referee were missed. This is partly due to the main search combinations which included the soil type and a hydrological term: e.g. (Vertisol or vertosol or cracking clay) and (groundwater or aquifer or recharge or preferential). Nevertheless the referee's citations contribute to the review and were included (lines 128-132; 280-289).

4) The authors define and limit the scope of the review, especially in lines 15-21. A limited scope is necessary for a broad and much-studied subject as the hydrology of vertisols. However, even with the four chosen subtopics, the treatment here is less complete and less fully developed than is needed for a major hydrologic journal. It should be extensively augmented, perhaps with a further-reduced topical scope, to be a good review article in HESS.

4) We disagree with the referee suggestion to reduce the topical scope and to augment on a narrower range of phenomenon. This review concerns only soil-aquifer phenomenon and it does not aim to be a general view on the hydrology of vertisols: topics like surface run off and erosion are not discussed, nor details of classical porous medium characteristics of these clays (e.g. hydraulic functions). Phenomena related to soils are often neglected by hydrogeologists when investigating aquifer dynamics (salinization, and other spatial and temporal trends in water levels and quality). As described in this review article, in cracking clays some phenomenon are more intense due to the more complex flow of water and gases and transport of solute through this type of soil, and the more dramatic change in the flow regime that is caused by cultivation, therefore a topical review discussing these phenomenon is worthwhile. The fourth chapter concerning nitrate contamination is less connected to flow and transport regimes in vertisols, yet it covers a topic that is of most interest worldwide – trends in contamination of aquifers with nitrate, and recently a few works showing a similar trend were reported. Therefore we thought it is valuable to include it in the review as it is certainly a soil-aquifer phenomenon in which the clays make the difference.

Nevertheless, as suggested by the referee and accepting suggestions made by Referee # 1 the article is now more comprehensive in a few issues including: observation of deep drainage through lysimeters (section 2.1); evaporation through cracks (section 3); deep drainage after cultivation in rain-fed versus irrigated cultivated vertisols (Section 4).

5) To some extent the paper progresses toward particular conclusions, such as the inhibition of nitrate transport, and discussion of causes and implications. In this way it reads less like a review paper and more like the discussion section of a paper on a more specific topic. This manuscript could be recast as a different sort of paper. It would be

possible to build a paper around the issues it concludes with, without the comprehensiveness of a review paper. But because this manuscript has very little unpublished original research, this direction would require considerable effort.
A review article on these topics with a much deeper and more detailed reach into the existing literature would be an extremely valuable contribution. In addition to a more thorough treatment of previous work, it would be very useful to make comparisons between preferential flow through cracks in vertisols and preferential flow through the macropores of other sorts of soils. I recommend that the authors pursue this course, with reductions of scope as necessary.

5) We agree with the referee that the paper does not read as a comprehensive review in some parts. The nitrate section, especially has a relatively high discussion/citation ratio as acknowledged by the referee, also due to the fact that there are not many publications that deal with the comparison of nitrate contamination in aquifers under different soils.
As of a comparisons between preferential flow through cracks in vertisols and preferential flow through the macropores of other sorts in soils, section 2.3 points out the development of mobile-immobile models first in the general dual domain of soil porosity that are used also for cracking clays and the further development to more crack specific models. We do not think a general comparison between the different types of macropore phenomena will sharpen the significance of the common and important soil-aquifer phenomenon in vertisols we review in this paper.

6) Following are minor comments, referenced by page and line number.
9576/21 – The section is limited to solute transport, so the heading would be better as "Preferential solute transport in vertisols."

6)Collides facilitated transport is reported as well, hence we prefer not limit to solute transport in the section title.

7) 9576/27-28 – What sort of VZ propagation, as contrasted with transport to groundwater?

7) The next sentence in the text explains:" Bronswijk et al. (1995) concluded that large cracks control the rapid transport of Br^- to the groundwater, and preferential paths made up of tortuous "mesopores" control transport in the unsaturated zone .

8) 9577/15-16 – What were the K values? How determined?

8) $6.2*10^{-8}$ cm/s for the clay matrix measured with a remolded cylinder by a standard rising tail water method.
$4.2*10^{-5}$ – $2.8*10^{-4}$ equivalent hydraulic conductivities derived from tracer peak arrival time, porosity and surface area and depth of lysimeter.

9) 9578/17-20 – Awkward sentence. Reorganize.

9)Thanks, the sentence was reorganized and split to 2 sentences in the revised manuscript (lines 216-220)

10) 9578/26 – More critical than what?

10) The word more was deleted. The mainstream mechanistic modeling approach for unsaturated flow is with the Richards Equation (HYDRUS and other codes). The Kinematic Wave formulation (e.g. MACRO) is another approach and Beven and Germann (2013) are critical on the mainstream Richards equation approach. Therefore the interested reader is referred to this critical review rather than the other more comprehensive reviews (and maybe biased towards the Richards Equation).

11) 9583/22 – Citation of research from a personal communication is inappropriate for a review article.

11) *There are seldom data dealing with nitrate concentrations in groundwater of the same aquifer analyzed with respect to the soil above the well area (that include vertisols). I happened to see this work of Dafny E. upon personal communication, unfortunately the work was not published yet, therefore I asked Dafny E. if I can mention the work under personal communication. Since now days communication is easy the motivated reader can easily locate the referred person, for more details. Therefore we prefer to include the reference, although it is not ideal.*

12) Adams, J.E., and R.J. Hanks. 1964. Evaporation from Soil Shrinkage Cracks. Soil Science Society of America Journal 28(2):281-284. 10.2136/sssaj1964.03615995002800020043x.
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12) Thanks for the references

Soil-Aquifer Phenomena Affecting Groundwater under Vertisols: a Review

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Abstract

Vertisols are cracking clayey soils that: i) usually form in alluvial lowlands where normally, groundwater pools into aquifers; ii) have different types of voids (due to cracking) which make flow and transport of water, solutes and gas complex, and iii) are regarded as fertile soils in many areas. The combination of these characteristics results in the unique soil–aquifer phenomena that are highlighted and summarized in this review. The review is divided into the following four sections: 1) Soil cracks as preferential pathways for water and contaminants; in this section lysimeter- to basin-scale observations that show the significance of cracks as preferential flow paths in vertisols which bypass matrix blocks in the unsaturated zone are summarized. Relatively fresh-water recharge and groundwater contamination from these fluxes and their modeling are reviewed; 2) Soil cracks as deep evaporators and unsaturated-zone salinity; deep sediment samples under uncultivated vertisols in semiarid regions reveal a dry (immobile), saline matrix, partly due to enhanced evaporation through soil cracks. Observations of this phenomenon are compiled in this section and the mechanism of evapoconcentration due to air flow in the cracks is discussed; 3) Impact of cultivation on flushing of the unsaturated zone and aquifer salinization; the third section examines studies reporting that land-use change of vertisols from native land to cropland promotes greater fluxes through the saline unsaturated-zone matrix, eventually flushing salts to the aquifer. Different degrees of salt flushing are assessed as well as aquifer salinization on different scales, and a comparison is made with aquifers under other soils; 4) Relatively little nitrate contamination in aquifers under vertisols; In this section we turn the light on

observations showing that aquifers under cultivated vertisols are somewhat resistant to groundwater contamination by nitrate (the major agriculturally related groundwater problem). Denitrification is probably the main mechanism supporting this resistance, whereas a certain degree of anion-exchange capacity may have a retarding effect as well.

Keywords: groundwater under vertisols; cracking clays; groundwater salinization

1. Introduction

Vertisols can be briefly defined as soils with 30% or more clay to a depth of 50 cm that have shrinking/swelling properties (Brady and Weil, 2002). More detailed definitions require the existence of a subsurface vertic horizon in which slickenside features are formed by the shrink/swell dynamics (FAO Corporate Document Repository, 2014; IUSS Working Group WRB, 2014). Other names used for these types of soils are: vertosols (common in Australian studies, e.g. Radford et al., 2009; Silburn et al., 2009; Gunawardena et al., 2011; Ringrose-Voase and Nadelko, 2013), and the more general 'cracking clays' (e.g. Bronswijk, 1991; Liu et al., 2010). This latter generic term emphasizes both the hydrological complexity of these soils due to the inherent discontinuities (cracks) and their relevance for agriculture, being heavy, relatively fertile soils in many semiarid regions (good water-holding capacity, relatively higher organic content, etc.). Vertisols usually form in lowlands (Yaalon, 1997) where, typically, groundwater pools into alluvial aquifers. Hence, the interface between agricultural activity on these soils and the underlying groundwater resources is both complex and relevant. This review focuses on vertisol studies that have implications for the underlying groundwater resources; it does not cover the substantial body of literature concerning shrinking/swelling dynamics and its modeling (e.g. Bronswijk, 1988; Chertkov et al., 2004; te Brake et al., 2013), the purely agricultural and mineralogical aspects of vertisols (e.g. Bhattacharyya et al., 1993; Ahmad and Mermut 1996; Hati et al., 2007) or environmental topics like the capacity of vertisols to sequester carbon (Hua et al., 2014).

Vertisols cover 335 million hectares out of a total earth land area of 14.8 billion hectares (2.3%). The largest areas covered with vertisols are in Eastern Australia, India, Sudan–Ethiopia and Argentina–Uruguay (FAO Corporate Document Repository, 2014). Smaller areas of vertisols are found in various countries (e.g. China, Israel, Mexico, Spain, Tunisia, USA, and many more). Although vertisols are very hard when dry, and very sticky when wet (making them difficult to till), in semiarid regions, irrigated crops such as cotton, corn, wheat, soybeans and others are grown on this soil. We acknowledge the dominant contribution of Australia to the literature on agro-hydrological aspects of vertisols. Conclusions from those studies have strengthened and generalized some of the findings obtained by the authors of this review in vertisol–groundwater studies in Israel, and have motivated this review (e.g. Arnon et al., 2008; Kurtzman and Scanlon, 2011; Baram et al. 2012a, 2012b, 2013, Kurtzman et al., 2013).

The review is divided into four sections which are partially connected and together deal with major issues concerning aquifers under agricultural land: recharge, salinization and nitrate contamination (other contaminants are mentioned as well). The following four sections cover the most general and relevant issues concerning soil-aquifers phenomena under vertisols:

- Soil cracks as preferential pathways for water and contaminants (section 2)
- Soil cracks as deep evaporators and unsaturated-zone salinity (section 3)
- Impact of cultivation on flushing of the unsaturated zone and aquifer salinization (section 4)
- The relatively little nitrate contamination in aquifers under vertisols (section 5)

2. Soil cracks as preferential pathways for water and contaminants

There are probably hundreds of studies that acknowledge preferential flow and transport through cracks in clays—too many to be mentioned here. This section aims to review works from the soil-column and lysimeter scale to the basin and aquifer scales that show the relations between preferential flow via cracks, deep drainage, and aquifer recharge and contamination. It also provides a short description of the development of models of preferential flow and transport through soil cracks.

2.1. Preferential flow of water in vertisols – evidence from the lysimeter to aquifer scale

On a small scale, Kosmas et al. (1991) observed bypass flow through cracks in clayey soils from Greece using undisturbed soil columns (authors' terminology) with a diameter of 23 cm. Ringrose-Voase and Nadelko (2013) measured flow in preferential paths directly using a field lysimeter that was installed 2 m below the surface of a furrow-irrigated cotton field without disturbing the overlying soil. Significant drainage was collected in this study when the hydraulic gradient in the matrix was in the upward direction, advocating drainage through preferential pathways that bypasses the matrix. In a paragraph on tension-lysimeters measurements, Silburn et al. (2013) acknowledge that: “deep drainage measured at 1m depth was dominated by matrix flow, with only 10% of drainage attributed to preferential flow (note that the soil was never dry enough to crack)”, pointing that under well-irrigated vertisols matrix deep-drainage and recharge may be of importance despite the low saturated hydraulic conductivity of the clay. A weighing-lysimeter experiment in irrigated vertisols in eastern Australia revealed a complex drainage mechanism following spray irrigation, where only deep parts of the cracks act as preferential pathways for the drainage when the top soil is moist and uncracked (Greve et al., 2010).

On the field scale (~100–1000 m^2), a similar phenomenon—i.e. open cracks at depth when surface cracks are mostly sealed—was reported by Baram et al. (2012b) throughout the rainy season in Israel. These authors compared transient deep (up to 12 m) water-content data collected by vadose zone-monitoring systems (VMSs, Dahan et al., 2009) at various sites, including very sandy soils; the comparison showed that by far, the fastest propagation of wetting fronts in deep vadose zones is observed in cracking clays.

Ben-Hur and Assouline (2002) conducted measurements of runoff in a vertisol cotton field in Israel that was irrigated with a moving sprinkler irrigation system. They observed that the high infiltration of runoff through soil cracks limited the overall surface runoff from the field. Other field-scale vadose-zone studies reported that preferential flow through cracked clay enhances infiltration from rice paddies (Liu et al., 2004). Losses of up to 83% of the water to deep drainage (including preferential and\or matrix flows) during furrow irrigation of cotton and sugar cane in vertisols were reported (Raine and

Bakker, 1996; Dalton et al., 2001; Moss et al., 2001; Smith et al., 2005). Losses to deep drainage averaged 42.5 mm per irrigation (Smith et al., 2005), ranging from 50 to 300 mm/year (Silburn and Montgomery, 2001). Chen et al. (2002) and Bandyopadhyay et al. (2010) showed that the transition from flood to micro-sprinkler irrigation and careful scheduling of water-application rates can dramatically reduce water losses and contaminant transport due to deep drainage. Observation from groundwater supported this phenomenon: Acworth and Timms (2009) used nested piezometers and automated logging of groundwater levels and electrical conductivity to show evidence of shallow-aquifer (16 m depth) freshening (decrease in salinity) due to fast deep-drainage of irrigation water during the irrigation season.

At the small-watershed scale (~10,000 m^2), Pathak et al. (2013) indicated that runoff from vertisols is smaller than runoff from sandier soils (Alfisols) in an agricultural watershed near Hyderabad, India. The smaller runoff from the vertisols was attributed to preferential infiltration of local runoff into the soil cracks. Similar observations of minimal drainage and rapid recharge of shallow groundwater (~3 m) below a vertisol–shale watershed in Texas following rainstorms were reported by Allen et al. (2005) and Arnold et al. (2005). This process was most dominant during the first rainstorms when the cracks were fully developed (at the end of the dry season).

On the aquifer scale (100+ km^2), Kurtzman and Scanlon (2011) concluded that parts of the Israeli Coastal Aquifer overlaid by vertisols were fresh (before the influence of modern intensive cultivation) only due to recharge flow through preferential paths that bypassed the saline vadose-zone matrix. Dafny and Silburn (2014) reported that following the growing evidence of the feasibility of percolation through cracking clays, several recent studies have included a component of diffuse recharge in their assumptions or models of the Condamine River Alluvial Aquifer in Australia. This diffused recharge originates in deep drainage flowing through clay matrix and\or preferential paths.

2.2. Preferential transport in vertisols

In the last two decades, many transport studies with dyes and/or other conservative tracers (e.g. bromide, Br^-) have indicated the pervasiveness of deep preferential transport through cracks in vertisols. Bronswijk et al. (1995) sprayed a bromide solution on cracking clays in the Netherlands that overlay a shallow water table (~1 m from ground surface). The authors reported rapid (on the order of days after rain event) preferential transport of Br^- into the groundwater, and relatively fast (weeks to months) propagation within the vadose zone. Bronswijk et al. (1995) concluded that large cracks control the rapid transport of Br^- to the groundwater, and preferential paths made up of tortuous "mesopores" control transport in the unsaturated zone (suggesting that transport through vertisols could be described as a triple domain medium—macropores, mesopores and matrix). Van Dam (2000) used the Crack module in SWAP to model the aforementioned experiment. This effort improved fits to the observations (relative to a single-domain model), but the variability of Br^- in the unsaturated zone still could not be well reproduced. Lin and McInnes (1995) used dye to study and model flow in vertisols. They showed that infiltrating water passes first through the soil cracks and then into the soil matrix; they concluded that uniform flow through the soil cannot be used to describe the dye transport. A dye experiment in a soil column consisting of a sandy A horizon and a vertic clay B horizon showed preferential downward flow through the cracks in horizon B, bypassing more than 94% of the matrix (Hardie et al., 2011).

Kelly and Pomes (1998) estimated equivalent hydraulic conductivities from arrival times of Br^- and ^{15}N-labeled nitrate in gravity lysimeters installed above and under a clay pan in Missouri (USA). They reported equivalent conductivities that were four orders of magnitude higher than the saturated hydraulic conductivity of the clay matrix.

Unlike tracers used in experiments, fast transport of herbicides and pesticides is of concern in aquifers and drainage systems down gradient from cultivated fields. Graham et al. (1992) reported that in cultivated vertisols in California (USA), herbicides were only found deep below the root zone in samples taken from the cracks' walls and not within the matrix, suggesting rapid transport of herbicides through the cracks, either as solutes or on colloids. Transport of pesticides in preferential flow paths absorbed on colloids was also suggested for cotton fields on vertisols in Australia (Weaver et al., 2012). Early and deep drainage of herbicides from a lysimeter in cracking clays in the UK (early = well before reaching field capacity in the matrix) was reported by Harris et al. (1994). Similarly, fast arrival of herbicides to drains in cultivated clays was observed by Tediosi et al. (2013) on a larger scale (small catchment).

Due to the fact that in semiarid regions, vertisols are arable, agriculture-oriented settlements have developed on these soils. In many cases, these settlements include concentrated animal feeding operations (CAFOs), such as dairy farms. Arnon et al. (2008) reported deep transport (>40 m) of estrogen and testosterone hormones into the unsaturated zone under an unlined dairy-waste lagoon constructed in a 6-m thick vertisol in Israel. They concluded that deep transport of such highly sorptive contaminants can only occur by preferential transport. Baram et al. (2012a, 2012b) reported that preferential infiltration of dairy effluents through the cracks at the same site can transport water and solutes into the deep unsaturated zone. Locally, groundwater under dairy farm areas also shows relatively high concentrations of nitrate (Baram et al., 2014).

Fig. 1 provides a visual summary of sections 2.1 and 2.2. It shows the potential for matrix-bypassing groundwater recharge and pollution under vertisols. Passing the biogeo-active matrix enables both freshwater recharge and transport of reactive substances.

2.3. Development of flow and transport models in cracking clays

The field evidence described above motivated the development of quantitative methods to enable better predictions of flow and transport from ground surface to water table under vertisols. Nevertheless, modeling of unsaturated flow and transport as a dual (or multiple) domain in their different variants (e.g. mobile–immobile, dual-porosity, dual-permeability) did not develop exclusively to deal with cracking clays. Macropores such as voids between aggregates, or worm-holes, are the preferential-flow paths of interest in many agricultural problems. Computer codes for modeling unsaturated preferential flow include among others: MACRO (Jarvis et al., 1994) and nonequilibrium flow and transport in HYDRUS (Šimůnek and van Genuchten, 2008). For further information on the kinematic wave approach used in MACRO, the reader is referred to German and Beven (1985); for comparative reviews of the different models and codes see Šimůnek et al. (2003), Gerke (2006), Köhne et al. (2009) and Beven and Germann

(2013). The latter is critical of the common use of the Richards (1931) formulation in single- and multiple-domain unsaturated-flow simulators.

One of the earlier crack-specific unsaturated-flow models was developed by Hoogmoed and Bouma (1980), who coupled vertical (crack) and horizontal (into the matrix) 1D models using morphological data for parameterization of the linkage between the two flows. Novák et al. (2000) attached a FRACTURE module to HYDRUS in which a source term was added to the Richards Equation accounting for infiltration from the bottom of the fractures, bypassing matrix bulks. Van Dam 2000, added a crack sub-model to SWAP (van Dam et al., 2008) and Hendriks et al. 1999 used a code called FLOCR\AMINO, to study flow and transport phenomenon in shallow and cracked clayey unsaturated-zones in the Netherlands. A model of herbicide transport through the preferential paths was fitted successfully with the improved MACRO version 5.1 (Larsbo et al., 2005).

A more comprehensive dual-permeability module for 2D and 3D variably saturated models was introduced into HYDRUS much later (Šimůnek et al., 2012) following the formulations of Gerke and van Genuchten (1993). Coppola et al. (2012) took another step forward in modeling flow and transport in cracking clays by also introducing cracking dynamics (adopting formulation of Chertkov, 2005) into a dual-permeability flow and transport model.

3. Soil cracks as deep evaporators and unsaturated-zone salinity

Whereas during rain events or under irrigation, cracks are a concern in terms of loss of water and fertilizers and/or contamination of groundwater (section 2), under dry conditions, deep soil cracks are relevant for their evaporation capacity from deep parts of the soil column. Kurtzman and Scanlon (2011), Baram et al. (2013) and others have reported the low water content and high salinity typical of the sediment matrix under uncultivated vertisols. Deep chloride profiles under native-land vertisols often show an increase in salinity down to 1–3 m and a relatively constant concentration in deeper parts of the vadose zone (e.g. Radford et al., 2009; Kurtzman and Scanlon, 2011; Silburn et al., 2011). In the reported cases from Israel, water uptake by roots was limited to the upper 1 m of the soil profile and to the rainy season, therefore, could not fully explain the increase in salinization in the deeper layers. Deep cracks form an additional mechanism of deep evaporation that supports the chloride profiles and low water content in the matrix under vertisols.

Sun and Cornish (2005) used SWAT to model runoff and groundwater recharge at the catchment scale (~500 km^2) in a vertisolic catchment in eastern Australia. Considering water balances at this scale, they concluded that recharge models need to have a component that enables taking moisture out of the lower soil profile or groundwater during dry periods. Trees with roots in groundwater and deep soil cracks can maintain deep evaporation in long dry periods. Another, indirect observation that supports evaporation through cracks in vertisol was reported by Liu et al. (2010). In this work discrepancies between satellite and model estimates of soil water content in dry seasons in vertisols are assumed to be related to the extra evaporation through the cracks.

Both local- and higher-scale observations and analyses point to possible significant role of soil cracks as deep evaporators in dry periods.

Baram et al. (2013) suggested a conceptual model termed ‘Desiccation Crack-Induced Salinization’ (DCIS) based on previous work on subsurface evaporation and salinization in rock fractures (e.g. Weisbrod and Dragila, 2006; Nachshon et al., 2008; Kamai et al., 2009; Weisbrod et al., 2009). In DCIS, vertical convective flow of air in the cracks is driven by instability due to cold (and dense) air in the crack near the surface and warmer air down in deeper parts of the crack at night or other surface-cooling periods. The difference in the relative humidity between the invading surface air (low humidity) and the escaping air (high humidity) leads to subsurface evaporation and salt buildup (Fig. 2).

Earlier studies that support the significance of evaporation via cracks in vertisols through field and laboratory observations include: Selim and Kirkham (1970), Chan and Hodgson (1981) and Adams and Hanks (1964). The latter showed enhanced evaporation from crack walls due to increase in surface wind velocity, this is another mechanism (in addition to surface cooling described before) causing instability in the crack’s air, hence convection, evaporation and salt build up.

Leaching of salts from horizontal flow through the crack-network evident in salinity-rise in tail water of furrow-irrigated fields in cracking clays in California was reported by Rhoades et al. (1997). This Californian study acknowledge that this phenomenon was not observed in similar fields (crop and irrigation technique) in lighter soils with no cracks.

In many semiarid regions, deep matrix percolation under non-cultivated vertisols is very small due to the clay's high retention capacity and low hydraulic conductivity, root uptake of the natural vegetation in the rainy season, and further evaporation through cracks in dry periods. Low water content in the deeper unsaturated zone results in low hydraulic conductivities and makes aquifer recharge through matrix flow very small year-round. Matrix fluxes in the order of 1 mm/yr under the root/crack zone were reported in a number of studies (e.g. Silburn et al. 2009, Kurtzman and Scanlon 2011; Timms et al. 2012). These very low water fluxes contain the conservative ions (e.g. chloride) originating from 200-600 mm/yr of precipitation (with salts from wet and dry fallout) that enter the matrix at soil surface. Therefore a dry (relatively immobile) and salty deep unsaturated matrix, developed for centuries-millennia under these non-cultivated vertisols. Nevertheless, some fresh recharge to the underlying aquifer through preferential paths related to cracks during heavy rain events creates an anomaly whereby relatively fresh water in the aquifer (e.g. ~250 mg/l chloride, Kurtzman and Scanlon, 2011) lies beneath a salty and immobile unsaturated zone with pore-water chloride concentration of a few thousands of milligrams per liter (O'Leary, 1996; Kurtzman and Scanlon, 2011; Tolmie et al., 2011; Baram et al., 2013). River, mountain-front, paleo or other types of recharge may contribute, as well, to a situation where relatively fresh aquifer exists under a saline vadose zone.

4. Impact of cultivation on flushing of the unsaturated zone and aquifer salinization

The anomalous situation of fresh groundwater under a saline unsaturated zone found in some native-land vertisols in semiarid regions exists due to the efficient evapotranspiration by natural vegetation and cracks (making deep unsaturated matrix immobile and saline) and fresh groundwater recharge through preferential flow in cracks or other types of recharge. However, what happens when natural conditions are changed to less favorable for native-vegetation and soil cracks (e.g. cultivated land and more ever irrigated intensive cropping)? The answer is obvious: higher fluxes may develop in the unsaturated matrix which will flush salts and ultimately cause salinization of the underlying aquifer.

A large bulk of literature from eastern Australia has reported increased deep-drainage and leaching of salts, and in some cases, salinization of aquifers under cultivated vertisols. A typical increase in deep drainage from < 1 mm/yr under native conditions to 10 – 20 mm/yr under rain-fed cropping were reported by Silburn et al., 2009; Timms et al., 2012 and Young et al., 2014; whereas variable deep fluxes often in the 100's mm/yr range were reported for irrigated fields (mostly furrow-irrigated cotton,. Gunwardena et al., 2011; Silburn et al., 2013; Weaver et al., 2013). These deep fluxes desolate salts that accumulated in the vadose zone in the native-vegetation period, moving them down towards the water table (Fig. 3). Earlier studies reporting leaching of salts from the vadose zone after clearing of natural eucalyptus trees for cropping include Allison and Hughes (1983) and Jolly et al. (1989), who worked in semiarid zones in Southern Australia. In those studies, neither vertisols nor the role of soil cracks was mentioned; however, deep eucalyptus roots act similar to cracks to form a very saline and immobile deep-unsaturated-zone matrix which becomes more mobile and less saline after the land-use change. Timms et al. (2012) inferred, from combined soil and groundwater data, deep drainage and salt leaching after conversion to cropping under gray vertosols in the Murray–Darling Basin. Fresh groundwater was found in that study under shallower saline waters, strengthening the source of groundwater salinity from the vadose zone.

Scanlon et al. (2009) compared mobilization of solutes in the vadose zone after a change in the natural landscape to cultivated fields in three semiarid regions: Amargosa Desert (southwestern USA), Southern High Plains (central USA) and Murray Basin (southeast Australia). Flushing of chloride from the top 6–10 m of the vadose zone after cultivation was very clear (e.g. Fig. 3 in Scanlon et al., 2009). Flushing has been observed in many arid and semiarid regions, and not exclusively related to vertisols (e.g., Oren et al., 2004, in the arid Arava Valley, southern Israel). Nevertheless, salinization of an aquifer due to cultivation and salt mobilization may be more pronounced under vertisols due to: preferential flow paths related to soil cracks (enabling the native aquifer to be relatively fresh) and the cracks evaporative capabilities (making the native deep vadose zone more saline).

A good example of an aquifer in which vertisols made a difference is the Mediterranean Coastal Aquifer in Israel (Fig. 4). Although known as a coastal aquifer the phenomena discussed here are all a few km inland and are not related to seawater intrusions. The parts of this aquifer overlain by vertisols were salinized a few decades after intensive-cultivation, whereas the water in those parts of the aquifer overlain by cultivated loamy-sand is still potable (Kurtzman, 2011; Kurtzman and Scanlon, 2011; Fig. 4). Similar to the Murray–Darling Basin (Timms et al., 2012), the upper groundwater under vertisols in this aquifer were more saline than the deep groundwater (e.g., Fig. 1 in Baram et al., 2014). Identification of the source of the salt and the cause of the salinization in the deep unsaturated zone under vertisols and land-use change, respectively, contradicted previous works which attributed the salinization of these parts of the Israeli Coastal Aquifer to the intrusion of deep brines and intensive pumping (e.g., Vengosh and Ben-Zvi, 1994; Avisar et al., 2004). A different and shorter temporal trend that might also be interpreted in light of soils covering the recharge area is the response of groundwater salinity of the Israeli Coastal Aquifer to extreme precipitation (e.g. winter of 1991/1992): under vertisols, freshening of the aquifer (decrease in salinity) was generally observed due to recharge of freshwater through preferential paths, mostly under uncultivated parts; under loamy-sand soils, salinization of the aquifer was observed due to piston-flow recharge pushing relatively saline vadose-zone pore-water down to the water table (Goldenberg et al., 1996, interpreted by Kurtzman and Scanlon, 2011).

5. Relatively little nitrate contamination in aquifers under vertisols

Whereas the literature concerning salinization of aquifers and draining of salts from the vadose zone under cultivated vertisols is abundant, much less has been written about the contamination of groundwater by nitrate under these soils. Nitrate is the most problematic groundwater contaminant associated with agriculture worldwide (Jalali, 2005; Erisman et al., 2008, Burow et al., 2010; Vitousek et al., 2010; Kourakos et al., 2012). Both mineral nitrogen fertilizers (e.g. Kurtzman et al., 2013) and organic forms of nitrogen (e.g. Dahan et al., 2014) are often applied in excess with respect to the plants' ability to take up the nitrogen, leaving significant quantities of nitrate as a potential groundwater contaminant.

While in the previous sections aquifers under vertisols were shown to be vulnerable to salinization, due to the agricultural practice above, there is an increasing number of observations that indicate lesser nitrate contamination in groundwater under cultivated vertisols relatively to groundwater of the same aquifer located under cultivated land of lighter soils. Kurtzman et al. (2013), dealing with nitrate contamination problems of the Israeli Coastal Aquifer, show that at the groundwater basin scale (~ 2000 km^2) the contamination plumes of nitrate are present in the aquifer only under cultivated sandy-loams, whereas under cultivated vertisols seldom sporadic wells produce water with nitrate concentration above the drinking-water standard (Fig. 4). Dafny (2014), revealed, by chi-square analysis that groundwater under cultivated vertisols and thick clayey-alluvial unsaturated zone, are less likely than groundwater under coarser sediments, to get contaminated by nitrate in the Condamine Floodplain Aquifer in Australia.

In contrast to the relatively high capability of vertisols to reduce nitrate leaching from cultivated land both Baram et al. (2014) (Israel, Coastal Aquifer) and Dafny (2014) (Condamine Floodplain Eastern, Australia) acknowledge that concentrated animal feeding operations (CAFO) can be significant point sources of nitrate in vertisols as well. This might be due to incidental percolation of CAFO wastewater through the crack systems.

Silburn et al. (2013) indicate that modern deep drainage and any solutes are still migrating down through the unsaturated zone in vertisol-aluvial systems in Australia and the nitrate is accumulating in the unsaturated zone. Nevertheless in vertisols areas overlaying the Israeli Coastal Aquifer the rise in salinity and unsaturated flow and transport models, indicate that the cultivation effects reached the water table, yet nitrate contamination is not severe, suggesting other mechanism are responsible for the low levels of nitrate contamination.

Denitrification in clayey soils is thought to be the major reason for the reduced deep leaching of nitrate in semiarid climates; this reduction of nitrate to gaseous nitrogen is less likely to be significant in lighter soils (Sigunga et al., 2002; Baram et al., 2012b; Boy-Roura et al., 2013; He et al., 2013).

Jahangir et al. (2012) found that adding carbon to deeper soil horizons significantly enhances denitrification in those layers. Profiles of dissolved organic carbon (DOC) in deep vadose zones (down to 9 m below ground) under citrus orchards on thick vertisols versus sandy-loam in Israel were compared. Whereas DOC in the lighter soils was higher than 15 $mg/kg_{dry\ soil}$ only in the top 1 meter, in the vertisols it was above 30 mg/kg_{dry_soil} in the entire 9 m profile (Shapira, 2012). These latter two studies support the notion that denitrification in the root zone, and perhaps beyond, results in less nitrate problems in aquifers under cultivated vertisols than under lighter soils. Thayalakumaran et al. (2014) reported high DOC in shallow groundwater overlain by irrigated sugarcane corresponds with absence of nitrate in this aquifer in northeast Australia.

Denitrification in the root zone and deeper in the soil profile explains the small amount of nitrate leached to the groundwater under rice fields in clayey soils in California, USA (Liang et al., 2014). Shallow groundwater (<1.5 m) under cultivated vertisols (e.g. Netherlands) showed large variability (spatial and temporal) in nitrate concentration, probably due to the highly variable oxygen concentrations and therefore variability in nitrogen transformations in these systems (Hendriks et al., 1999).

A more speculative mechanism that might explain the relatively lower occurrence of groundwater nitrate contamination involves the anion-exchange capacity of the clay. Harmand et al. (2010) observed very significant adsorption of nitrate to kaolinite and oxyhydroxides under a fertilized coffee plantation growing on an acrisol in Costa Rica. In vertisols, montmorillonite is usually the dominant clay mineral; nevertheless, some kaolinite is found in most vertisols (e.g. Singh and Heffernan, 2002; Krull and Skjemstad, 2003; Baram et al., 2012b). Another drawback of this mechanism as dominant in vertisols is: adsorption of anions to positively charged surface is more efficient at low pH, while vertisols in semiarid regions are usually neutral to alkaline. Retardation of nitrate in the vadose zone due to adsorption to positively charged sites within the clay might slow down groundwater contamination under cultivated vertisols. Nevertheless, if significant, this mechanism would only retard groundwater contamination, whereas denitrification removes the nitrogen from the soil–unsaturated zone–aquifer system. The idea of nitrate adsorption has been tested as an engineered solution for reducing deep nitrate percolation. Artificially synthesized materials that have nitrate-sorption capacity (e.g. $[Mg^{2+}_{0.82}\ Al^{3+}_{0.18}\ (OH)_2]^{0.18+}[(Cl-)_{0.18} \cdot 0.5(H2O)]^{0.18-}$) are being tested as soil additives to buffer nitrate leaching (Torres-Dorante et al., 2009).

6. Conclusions

Vertisols are considered arable soils in semiarid climates, and are intensively cultivated. Located in lowlands, vertisols often overlie aquifers. Flow and transport through the cracking clays is complex and results in unique land–aquifer phenomena. Observations from the lysimeter to basin scale have shown (directly and indirectly) the significance of cracks as preferential flow paths in vertisols that bypass matrix blocks in the unsaturated zone. These preferential paths support recharge with relatively fresh water in uncultivated vertisols, and groundwater contamination from point sources such as CAFOs and under some conditions, from crop fields. Deep soil samples under uncultivated vertisols in semiarid regions reveal a dry (immobile), saline matrix, partly due to enhanced evaporation through the soil cracks. This evaporation is related to convective instability due to colder air at ground surface and warmer air deep in the crack during the night. In some aquifers lying beneath vertisols in these regions, relatively fresh groundwater exists under the saline unsaturated zone. Land-use change to cropland promotes greater fluxes through the saline matrix which flush salts into the aquifer and eventually cause groundwater salinization. In contrast to the vulnerability of groundwater under vertisols to salinization, observations show that this soil–aquifer setting has some resistance to groundwater contamination by nitrate (the major agriculturally related groundwater contamination). Denitrification is probably the main mechanism supporting this resistance, whereas anion-exchange capacity may have a retarding effect as well.

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Figure captions

Fig. 1. Illustration of potential fluxes of water and pollutants that bypass the matrix, which is typical of vertisols.

Fig. 2. Desiccation Crack-Induced Salinization (DCIS), Baram et al. (2013). Convective instability of air in soil cracks, occurring mainly at night, leads to drying and salinization of the unsaturated zone.

Fig. 3. Flushing of chloride down through the unsaturated zone under cultivated vertisols: (a) Silburn et al. (2009) – 19 years of flushing; (b) Radford et al. (2009) - full diamond, native vegetation; empty, annual cropping; flushing from the top 3 m (c) Kurtzman and Scanlon, (2011) – red, natural land; blue, irrigated cropping; flushing from 2 -10 m depth; (d) Tolmie et al. (2011) –flushing from the top 1.5 m. (e) Timms et al. (2012) - black, cropping; empty - grass; flushing from the top 2 m.

Fig. 4. Plan views of the Israeli Coastal Aquifer. (a) Soil type (black polygons and red ellipses for spatial comparisons with panels d and e, respectively). (b) Location map. (c) Cultivated land in the year 2000. (d) Difference in chloride concentrations between 2007 and 1935 (modified from Livshitz and Zentner, 2009). Black polygons are characteristic cultivated areas that were severely salinized (southern polygons) and barely salinized (northern polygon) relative to soil type (panel a). (e) Nitrate concentration in groundwater wells in 2007 (modified from Hydrological Service, 2008). Red ellipses – areas with many wells contaminated with nitrate relative to soil type (panel a) (modified from Kurtzman et al., 2013).

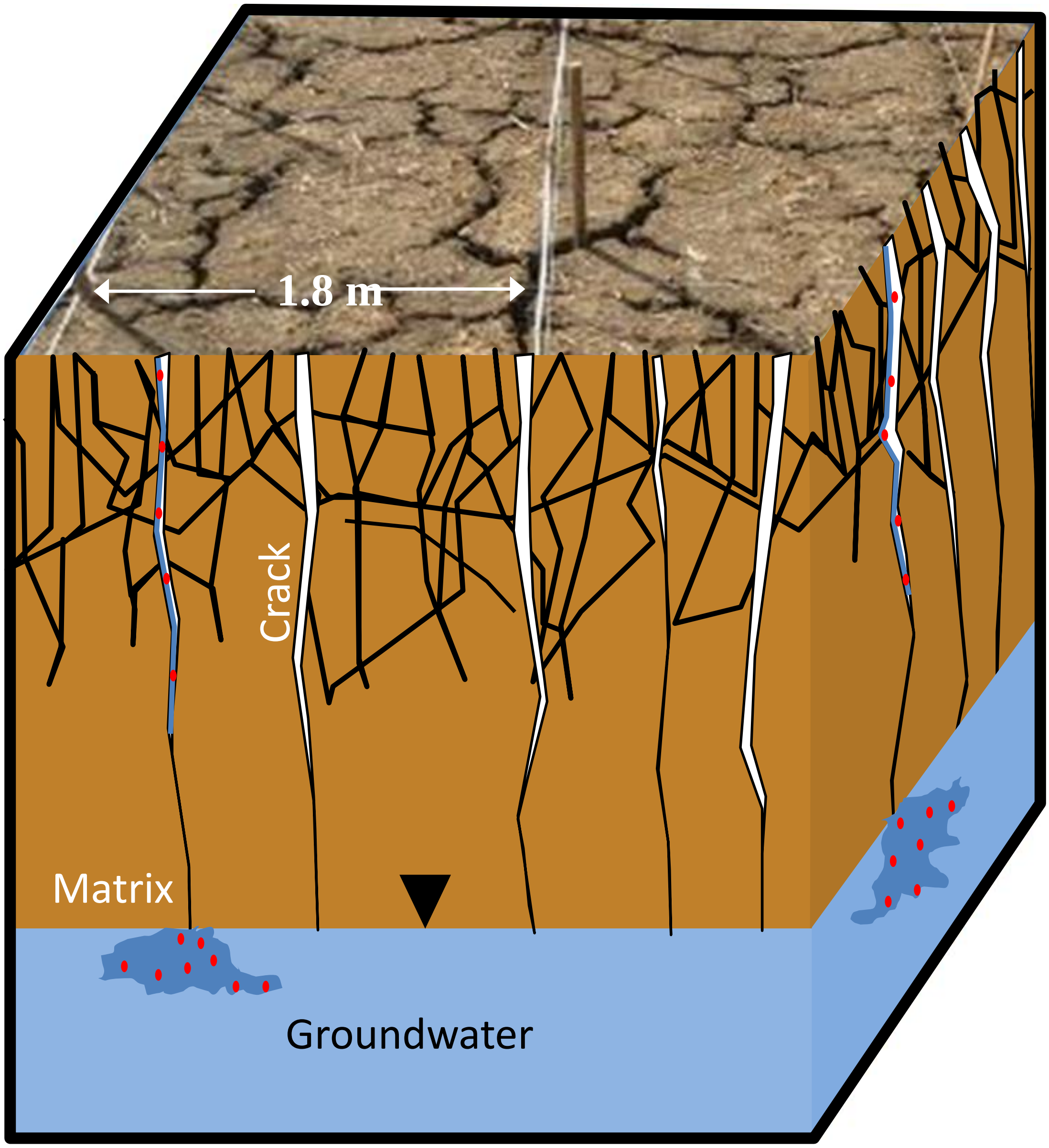


Fig. 1

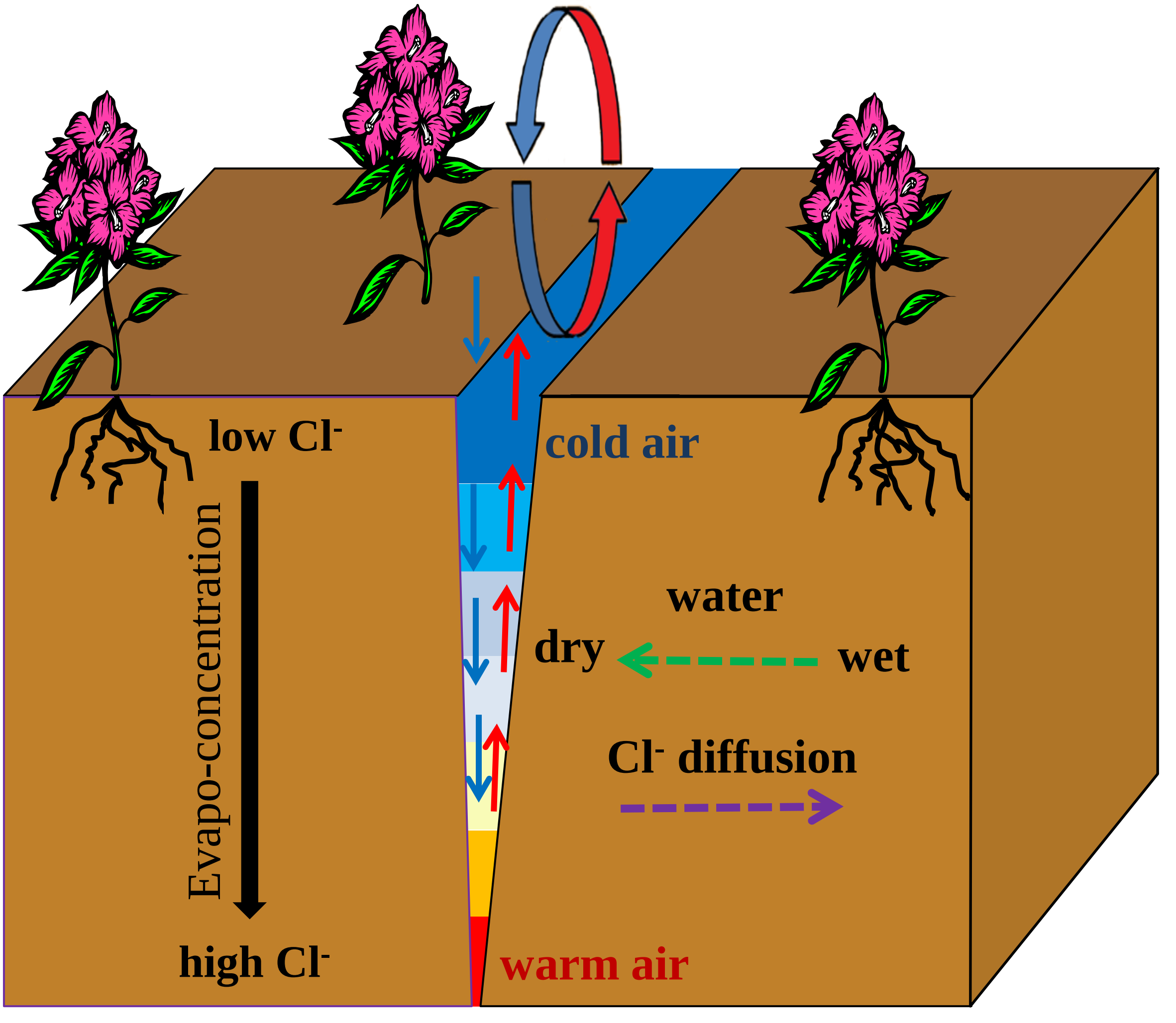
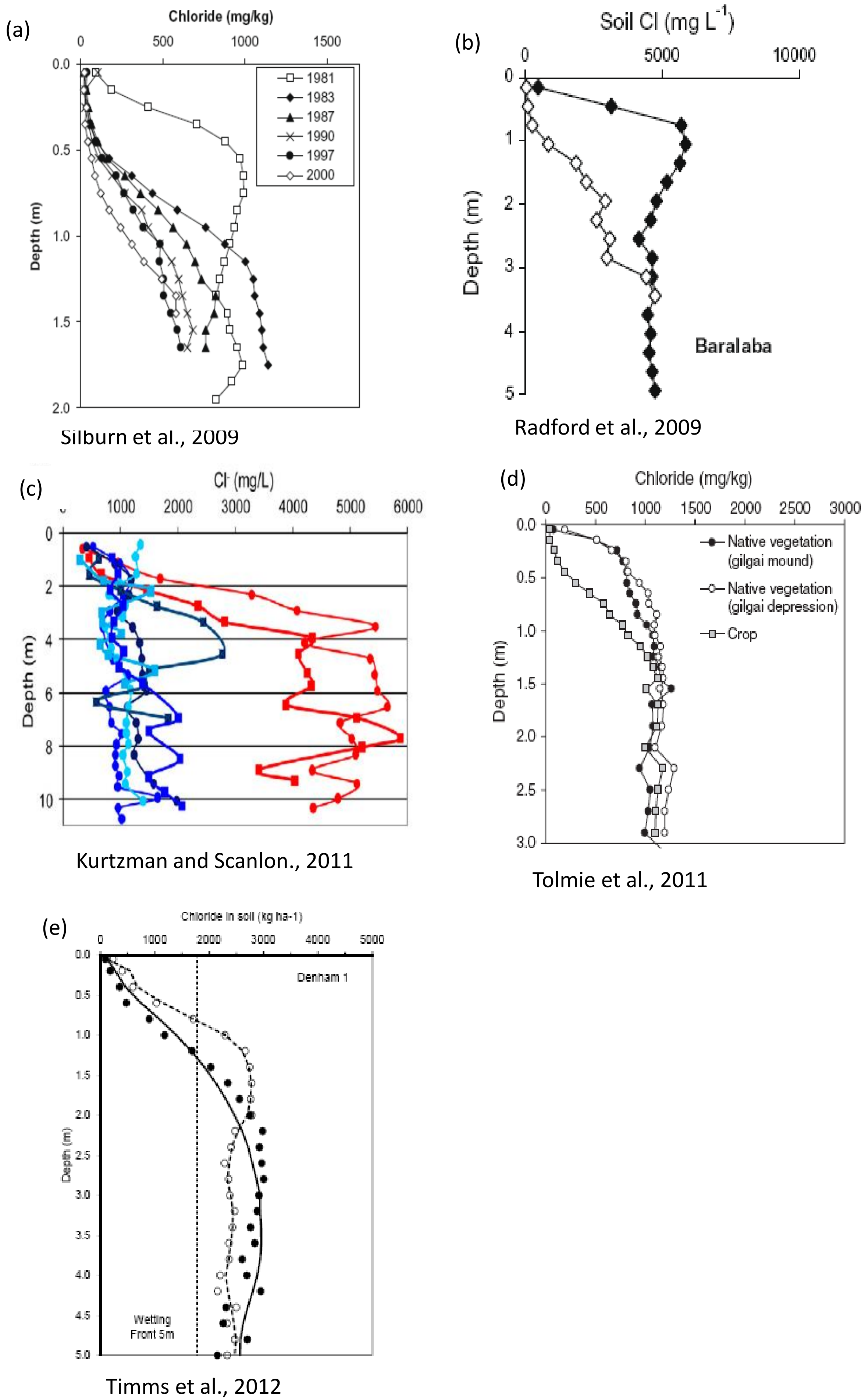
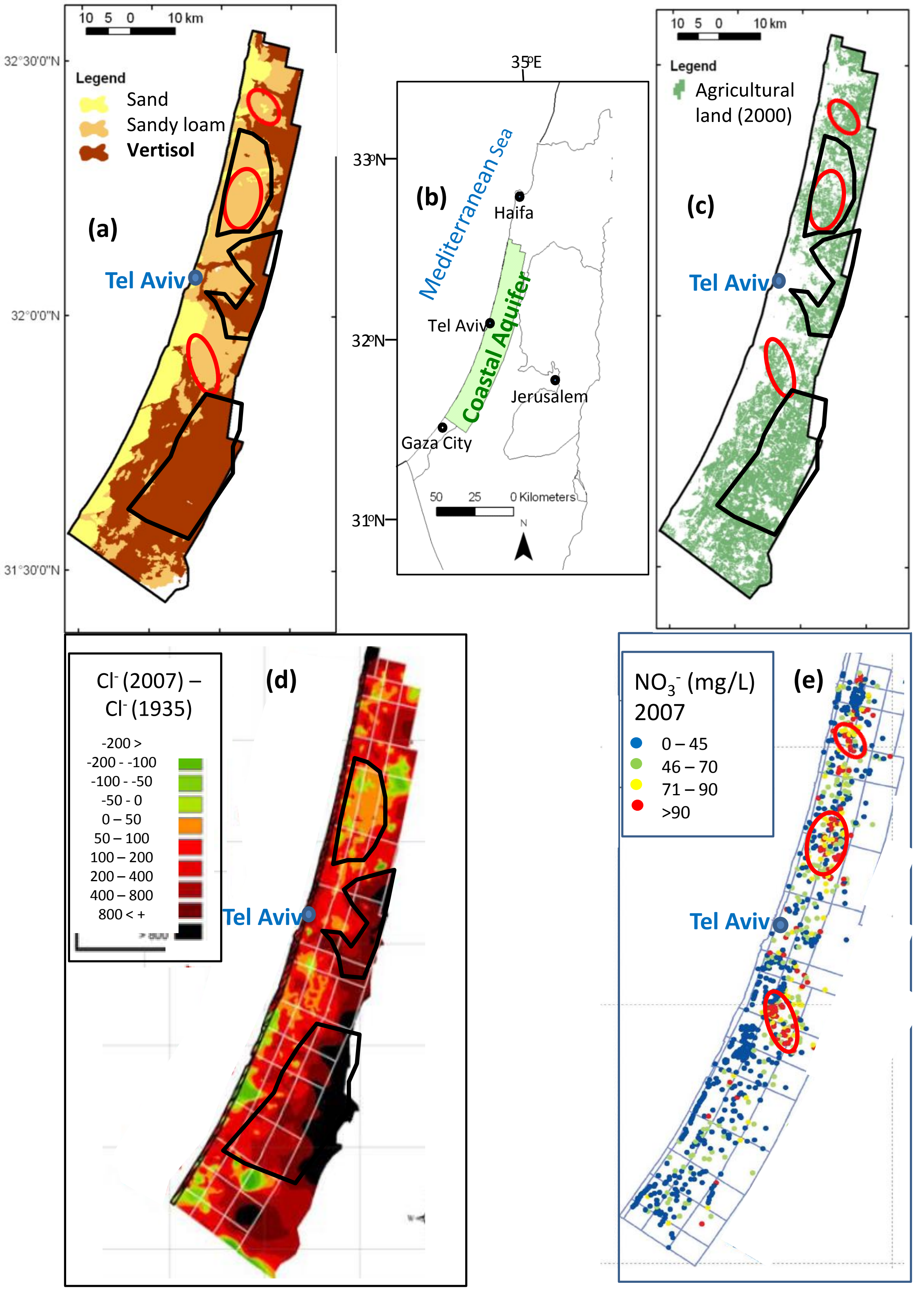

low Cl-
Evapo-concentration
high Cl-
cold air
water
dry
wet
Cl- diffusion
warm air

Fig. 2



(a)
Chloride (mg/kg)
0
500
1000
1500
0.0
0.5
1.0
1.5
2.0
Depth (m)
1981
1983
1987
1990
1997
2000
Silburn et al., 2009
(b)
Soil Cl (mg L-1)
0
5000
10000
Depth (m)
Baralaba
Radford et al., 2009
(c)
Cl- (mg/L)
1000
2000
3000
4000
5000
6000
Depth (m)
Kurtzman and Scanlon., 2011
(d)
Chloride (mg/kg)
0
500
1000
1500
2000
2500
3000
Depth (m)
Native vegetation (gilgai mound)
Native vegetation (gilgai depression)
Crop
Tolmie et al., 2011
(e)
Chloride in soil (kg ha-1)
0
1000
2000
3000
4000
5000
Depth (m)
Denham 1
Wetting Front 5m
Timms et al., 2012

Fig. 3



10 5 0 10 km
32°30'0"N
32°0'0"N
31°30'0"N
Legend
Sand
Sandy loam
Vertisol
(a)
Tel Aviv
35°E
33°N
32°N
31°N
(b)
Mediterranean Sea
Haifa
Tel Aviv
Coastal Aquifer
Jerusalem
Gaza City
50 25 0 Kilometers
N
10 5 0 10 km
Legend
Agricultural land (2000)
(c)
Tel Aviv
Cl- (2007) – Cl- (1935)
-200 >
-200 - -100
-100 - -50
-50 - 0
0 – 50
50 – 100
100 – 200
200 – 400
400 – 800
800 < +
(d)
Tel Aviv
NO3- (mg/L) 2007
0 – 45
46 – 70
71 – 90
>90
(e)
Tel Aviv

Fig. 4