Are Global Environmental Uncertainties Inevitable?
Measuring Desertification for the SDGs

Supplementary Material

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Supplementary Information

Modelling the transition to quantifiable uncertainty

The Uncertainty Assessment Framework (UAF) has been devised to evaluate in a largely qualitative way very large uncertainties, of the kind associated with global environmental change phenomena, However, it is possible to trace continuity and consistency between the UAF and existing methods for characterizing environmental uncertainties, by using the UAF to model how uncertainties should ideally decline over time as knowledge accumulates, eventually reaching a level where they can be evaluated using standard quantitative methods.

Focusing on present uncertainty, let the ultimate gap between complete knowledge (K_c) and present knowledge (K_t) be divided into three of Wynne's kinds of uncertainty: (a) uncertainty proper, which can be reduced; (b) indeterminacy, which cannot; and (c) ignorance, which can only be partly reduced [26]. Since Wynne himself described his kinds of uncertainty as "overlaid", not compartmentalized, let us further assume that only as K_t approaches K_c might the boundaries between uncertainty, ignorance and indeterminacy become as clearly defined as they are in Supplementary Figure S1. If at some arbitrary *limiting knowledge* (K_l) the difference between K_c and K_l is reasonably approximated by the sum of limiting uncertainty (U_l), irreducible ignorance (I_l), and indeterminacy (D), then equation (1) in the main text becomes:

$$K_c = K_l + U_l + I_l + D \qquad \text{(i)}$$

Addressing *conceptualization uncertainty* at time t (U_{ct}) first, proxies uncertainty (U_{cprt} in equation (4) in the main text) should disappear as theories mature and direct measurement improves, so that proxies are no longer needed. As K_t approaches K_l, U_{ct} should decline to a limiting value U_{cl}. Most of U_{cl}, comprising the sum of U_{ctel} and U_{cuspl}, can then be described by the ultimate inability to "know what we don't know" [26], i.e. irreducible ignorance (I_l). Taking a middle way between the interpretations of indeterminacy by Wynne [26] and Eddington [27] (see Section 2.1), the other part of U_{cl}, i.e. U_{custl}, could contribute to indeterminacy (D_c) to allow for synergies between conceptualization and measurement. So conceptualization uncertainty could move to a limit of:

$$U_{cl} = I_l + D_c \qquad \text{(ii)}$$

Concerning *measurement uncertainty,* subjective estimates (U_{msu} in equation (5) in the main text) should disappear first as scientists assert their autonomy to measure the planet directly. As K_t approaches K_l scalar deficiencies uncertainty (U_{msc}) could move toward a limiting value, U_{mscl}, which reflects science's ultimate inability to devise technologies and institutions for global measurement and estimation, and this should account for most indeterminacy (D_m). Random errors (U_{mr}) should decline to a limiting value of U_{mrl}. Systematic errors (U_{msy}) should also decline to a limiting value of U_{msyl}, because sampling designs will improve and wall-to-wall measurement will increase; the use of inappropriate technologies will become inconsistent with evolving disciplinary institutions; and constraints on measurement from political institutions will also decline. So measurement uncertainty could move to a limit of:

$$U_{ml} = U_{mrl} + U_{msyl} + D_m \qquad \text{(iii)}$$

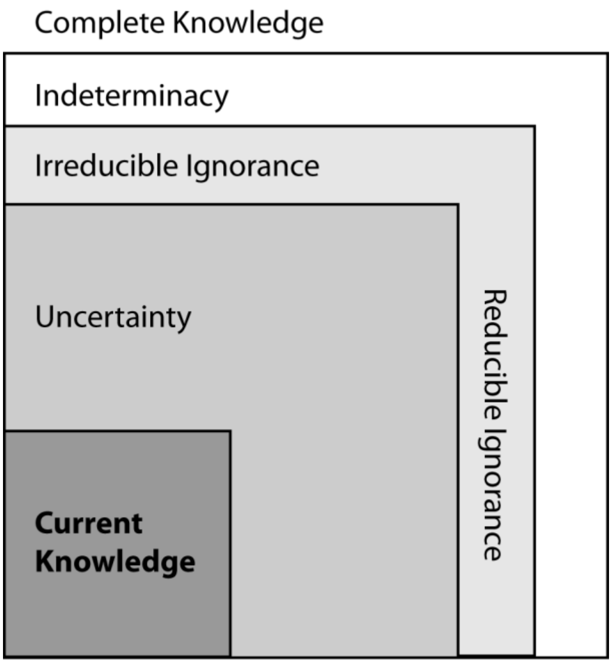
Substituting these limiting values for K_t, U_{ct} and U_{mt} in equation (1) :

$$K_c = K_l + (I_l + D_c) + (U_{mrl} + U_{msyl} + D_m) = K_l + (U_{mrl} + U_{msyl}) + I_l + D \qquad \text{(iv)}$$

where $D = D_c + D_m$.

Comparing equations (i) and (iv) indicates three things about the UAF. First, it is consistent with Wynne's [26] taxonomy of kinds of uncertainty. Second, it displays continuity with existing quantitative methods for uncertainty assessment. Third, the use of quantitative methods becomes more appropriate as limiting knowledge is approached, for by then the limiting uncertainty (U_l) in equation (i) will be the sum of uncertainties due to random errors (U_{mrl}) and systematic errors (U_{msyl}). Remaining uncertainty will comprise irreducible ignorance and indeterminacy.

Supplementary Figure S1. The gap between complete knowledge and present knowledge at limiting uncertainty, based on Wynne [26].



Supplementary Table S1. Dominant topic areas of 96 papers in *International Journal of Remote Sensing* Volume 30, Issues 17-18 and 21-24 in 2009.

Topic	Number of papers	Percent	Scalar notes
Classification	33	34	
Mapping	28	29	Global = 1
Modelling	17	18	
Radiance and reflectance studies	6	6	Regional = 1
Sensor evaluation	6	6	
Pre-processing applications	4	4	
Validation	2	2	
Total	96	100	

References for Supplementary Table S1

Classification

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Supplementary Table S2. A taxonomy of sources of environmental uncertainty proposed by Regan et al. (2002) [13].

Linguistic

L1. Vagueness - use of terms or statements in natural and scientific language allows borderline cases

L2. Context dependence - failing to clearly specify the context in which a proposition is understood

L3. Ambiguity - the same term has different meanings for different scientists

L4. Underspecificity - statements lack detail, often because of poor data

L5. Indeterminacy - theoretical terms used without accepted definitions, future ambiguity possible

Epistemic

E1. Measurement error - limitations of equipment or human error

E2. Systematic error - bias in equipment or sampling design

E3. Natural variation - unpredictable spatial and/or temporal variation

E4. Inherent randomness - unpredictable because relationships are hard to specify

E5. Model uncertainty - limitations of models due to a restricted set of variables

E6. Subjective judgment in interpreting data in data poor situations

Supplementary Table S3. A taxonomy of sources of environmental uncertainty proposed by Van Asselt and Rotmans (2002) [17].

Variability

V1. Inherent randomness - non-linear, chaotic and unpredictable natural processes

V2. Value diversity - differences in people's mental maps, world views and norms

V3. Human behaviour which deviates from rational standards

V4. Societal dynamics - non-linear, chaotic and unpredictable societal processes

V5. Technological surprises - unexpected consequences of technology

Limited Knowledge

K1. Inexactness - lack of precision, inaccuracy

K2. Lack of observations/measurements - lack of data that could have been collected

K3. Practically immeasurable - data shortages result from impracticality of measurements

K4. Conflicting evidence - available data allow conflicting interpretations

K5. Reducible ignorance - data shortages could end if processes are observed and theorized

K6. Indeterminacy - processes can never be fully predicted or determined

K7. Irreducible ignorance - processes can never be unambiguously determined

Supplementary Table S4. Key features of 50 papers published in the journal *Land Degradation and Development* between 2006 and 2010 (Volumes 17-21) that assessed dryland degradation (for detailed sources see Supplementary Table S5).

	Number of papers
Words included in the title:	
Desertification	2
Degradation	12
Erosion/erodibility	17
Soil loss	1
Gully	1
Salinity	4
Climate/precipitation	2
None of these	11
Total	50
The word 'desertification' included in the text:	
Yes	18
No	32
Total	50
Remote sensing methods used in the paper:	
Low resolution satellite images	3
Medium resolution satellite images	5
Aerial photographs	5
Aerial photographs + medium resolution satellite images	2
Total	15

Supplementary Table S5. Mapping, modelling and linguistic preferences in a sample of 50 papers in *Land Degradation and Development* between 2006 and 2010 on assessing land degradation. This shows the use of remote sensing and the resolution of satellite sensors (low or medium); collection of data by sampling; key words in the titles of papers; reference to 'desertification' in the text of papers; and the modelling of land degradation risk. For full references see Supplementary Table S9.

Author	**Date**	**Discipline**	**Remote sensing**	**Sensor type**	**Sampling**	**Title words**	**Desert-ification**	**Risk model**
Anley et al.	2007	Agronomy	no	-	yes	degradation	-	-
Bou Kheir	2008	Remote sensing	yes	medium	no	erosion	-	yes
Brunner et al.	2008	Geography	no	-	yes	erosion	-	yes
Butt	2010	Environmental management	yes	medium	yes	-	-	-
Castrignano et al.	2008	Agronomy	no	-	yes	erodibility	-	yes
Constantini et al.	2009	Soil science	no	-	yes	desertification	yes	yes
De Luis et al.	2010	Geography	no	-	yes	precipitation	yes	yes
De Oro and Buschiazzo	2009	Agronomy	no	-	yes	erosion	-	-
Dragovich and Dominis	2008	Geography	yes	aerial photo	yes	salinity	-	-
Enfors and Gordon	2007	Ecology	yes	medium	no	-	-	-
Feng et al.	2009	Remote sensing	yes	medium	-	degradation	yes	-
Gutierrez et al.	2009	Geography	yes	aerial photo	yes	gully erosion	-	-
Hein	2007	Environmental management	no	-	yes	degradation	-	-
Homann et al.	2008	Agronomy	no	-	yes	-	-	-
Huading et al.	2007	Geography	yes	low	no	erosion	yes	yes
Keay-Bright and Boardman	2007	Environmental management	no	-	yes	erosion	yes	-
Khan and Hanjra	2008	Agronomy	no	-	yes	-	-	yes
Kiunsi and Meadows	2006	Environmental science	yes	aerial photo + medium	no	degradation	yes	-
Klintenberg and Verlinden	2008	Geography	no	-	yes	-	-	-
Li et al.	2007	Environmental science	yes	aerial photo	no	desertification	yes	-
Li et al.	2009	Remote sensing	yes	medium	-	degradation	yes	-
Lopez-Vicente and Navas	2010	Soil science	no	-	yes	erosion	-	-

Supplementary Table S5 (Contd….)

Mairura et al.	2008	Agronomy	no	-	yes	-	-	-
Marques et al.	2010	Agronomy	no	-	yes	erosion	-	-
Martinez Raya et al.	2006	Agronomy	no	-	no	erosion	-	-
Milgroom et al.	2007	Agronomy	no	-	yes	erosion	-	yes
Moges and Holden	2007	Agronomy	no	-	yes	erosion	-	-
Moges and Holden	2008	Agronomy	yes	aerial photo	yes	gully	-	-
Muleta et al.	2006	Environmental science	yes	aerial photo		erosion	-	
Navarro-Pedreno	2007	Agronomy	no	-	yes	salinity	-	-
Nyssen et al.	2008	Soil science	no	-	yes	-	-	-
Oba et al.	2008	Environmental management	no	-	yes	-	yes	-
Okayasu et al.	2007	Environmental science	yes	low	no	-	yes	-
Okayasu et al.	2010	Environmental science	no	-	no	degradation	yes	-
Okoba et al.	2007	Agronomy	no	-	yes	erosion	-	-
Omuto and Vargas	2009	Soil science	yes	medium	yes	soil loss	-	yes
Ramos and Martinez-Casanovas	2010	Environmental science	no	-	yes	erosion	-	-
Reed et al.	2007	Environmental management	no	-	no	degradation	yes	-
Robertson et al.	2009	Agronomy	no	-	yes	salinity	-	-
Romero-Diaz et al.	2010	Geography	no	-	yes	erosion	yes	-
Seeger and Ries	2008	Geography	no	-	yes	degradation	-	-
Stringer and Reed	2007	Environmental management	no	-	yes	degradation	yes	-
Stringer et al	2007	Environmental management	no	-	yes	degradation	yes	-
Sugimori et al.	2008	Agronomy	no	-	yes	salinity	-	-
Tenge et al.	2007	Agronomy	no	-	yes	-	-	-
Verlinden and Kruger	2007	Agronomy	yes	aerial photo	yes	-	-	-
Visser and Sterk	2007	Soil science	no	-	yes	erosion	-	-
Wei et al.	2009	Environmental management	no	-	yes	degradation	yes	-
West et al.	2008	Geography	no	-	yes	climate	yes	-
Zhang et al.	2007	Environmental science	no	-	no	degradation	yes	-

Supplementary Table S6. Six sets of indicators used to specify desertification (*= a proxy indicator).

Dregne [2,75]	Middleton & Thomas [3]	LADA [77]
Vegetation degradation	Agricultural suitability of land*	Aridity index
Water erosion	Agricultural productivity*	Rainfall variability
Wind erosion	Quality of terrain*	Soil moisture
Irrigated crop yields*	Intactness of biotic functions	Soil health
	+ Ease of restoration*	Soil loss
		Soil salinity
Dregne [1]		Soil fertility
		Vegetation activity
Vegetation degradation		Water availability
Soil erosion		Groundwater level
Irrigated crop yields*		Water salinity
Mabbutt [56]		LADA [57]
Livestock yields*		Vegetation productivity*
Rainfed crop yields*		
Irrigated crop yields*		

Supplementary Table S7. Sizes of "degrading area" in drylands by climatic zone in the original study [68] on which the Land Degradation Assessment in Drylands (LADA) “preliminary [global] map of land degradation” [57] is based.

Climatic zone	Area (Mha)
Dry sub-humid zone	280
Semi-arid zone	316
Arid and Hyper-arid zones	175
All drylands	771
All lands in the world	3,506

Supplementary Table S8. Scalar foci of a sample of 50 papers published in *Land Degradation and Development* between 2006 and 2010 (Volumes 17-21) that assess dryland degradation, showing percentages of papers by: the actual scale they use for conceptualization, the ideal scale for conceptualization, the scale at which they collected data, and the scale at which they produce information (for detailed sources see Supplementary Table S9).

	Conceptualization		Data	Information
	Ideal	Actual	Collected	Produced
Global	-	-	-	-
Regional	-	-	-	-
National	4	4	4	4
Regional	16	16	4	16
District	34	34	16	36
Catchment	26	26	6	26
Village	2	2	12	2
Farm	16	16	26	14
Household	0	0	2	0
Plot	2	2	30	2
Total	100	100	100	100

Supplementary Table S9. Scalar preferences in a sample of 50 papers in *Land Degradation and Development* between 2006 and 2010 on assessing land degradation.

			Conceptualization		Scale of	Scale of
Author	**Date**	**Discipline**	**Ideal**	**Actual**	**Information**	**Data**
Anley et al.	2007	Agronomy	farm	farm	farm	farm
Bou Kheir	2008	Remote sensing	district	district	district	district
Brunner et al.	2008	Geography	catchment	catchment	catchment	catchment
Butt	2010	Environmental management	district	district	district	village
Castrignano et al.	2008	Agronomy	district	district	district	plot
Constantini et al.	2009	Soil science	national	national	national	national
De Luis et al.	2010	Geography	region	region	region	region
De Oro and Buschiazzo	2009	Agronomy	farm	farm	farm	plot
Dragovich and Dominis	2008	Geography	district	district	district	plot
Enfors and Gordon	2007	Ecology	district	district	district	district
Feng et al.	2009	Remote sensing	district	district	district	district
Gutierrez et al.	2009	Geography	catchment	catchment	catchment	plot
Hein	2007	Environmental management	catchment	catchment	catchment	farm
Homann et al.	2008	Agronomy	region	region	region	villages
Huading et al.	2007	Geography	region	region	region	region
Keay-Bright and Boardman	2007	Environmental management	farm	farm	district	farm
Khan and Hanjra	2008	Agronomy	region	region	region	farm
Kiunsi and Meadows	2006	Environmental science	district	district	district	district
Klintenberg and Verlinden	2008	Geography	district	district	district	site
Li et al.	2007	Environmental science	district	district	district	district
Li et al.	2009	Remote sensing	catchment	catchment	catchment	catchment
Lopez-Vicente and Navas	2010	Soil science	catchment	catchment	catchment	plot
Mairura et al.	2008	Agronomy	district	district	district	farm
Marques et al.	2010	Agronomy	farm	farm	farm	plot

Supplementary Table S9 (Contd….)

Martinez Raya et al.	2006	Agronomy	plot	plot	plot	plot
Milgroom et al.	2007	Agronomy	farm	catchment	farm	farm
Moges and Holden	2007	Agronomy	catchment	catchment	catchment	farm
Moges and Holden	2008	Agronomy	catchment	catchment	catchment	farm
Muleta et al.	2006	Environmental science	catchment	catchment	catchment	catchment
Navarro-Pedreno	2007	Agronomy	region	region	region	sites
Nyssen et al.	2008	Soil science	catchment	catchment	catchment	plot
Oba et al.	2008	Environmental management	district	district	district	village
Okayasu et al.	2007	Environmental science	district	district	region	region
Okayasu et al.	2010	Environmental science	district	district	district	district
Okoba et al.	2007	Agronomy	catchment	catchment	catchment	farm
Omuto and Vargas	2009	Soil science	district	district	district	district
Ramos and Martinez-Casanovas	2010	Environmental science	farm	farm	farm	plot
Reed et al.	2007	Environmental management	village	village	village	household
Robertson et al.	2009	Agronomy	catchment	catchment	catchment	farm
Romero-Diaz et al.	2010	Geography	catchment	catchment	catchment	plot
Seeger and Ries	2008	Geography	region	region	region	plot
Stringer and Reed	2007	Environmental management	local	local	district	local
Stringer et al	2007	Environmental management	region	region	region	farm
Sugimori et al.	2008	Agronomy	farm	farm	farm	plot
Tenge et al.	2007	Agronomy	catchment	catchment	agronomy	farm
Verlinden and Kruger	2007	Agronomy	region	region	region	village
Visser and Sterk	2007	Soil science	village	village	village	plot
Wei et al.	2009	Environmental management	farm	farm	farm	farm
West et al.	2008	Geography	district	district	district	households
Zhang et al.	2007	Environmental science	national	national	national	national

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