A new approach for forest decline assessments: maximizing detail and accuracy with multispectral imagery

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Remo e en ing of fo e condi ion i picall ba ed on b oadband ege a ion indice o q an if coa e ca ego ie of canop condi ion. Mo e de ailed and acc a e a e - men ha e been demon a ed ing na o band en o , al ho gh i h mo e limi ed image a ailabili . While diffe ence in en o capabili ie a e ob io , I h po he i ed ha m l i pec al image ma be able o de ec mo e b le canop e mp om if a ne calib a ion app oach a con ide ed. Thi in ol e h ee majo change o adi ional decline a e men : (1) calib a ion i h mo e de ailed field mea emen , (2) con ide a ion of na o band de i ed indice adap ed fo b oadband calc la ion, and (3) a m l i a ia e calib a ion model. Te ing hi app oach on Land a -5 (TM) image in he Ca kill , NY, USA, a fi e- e m linea eg e ion model (r^2 = 0.621, RMSE 0.403) ba ed on a niq e combina ion of ege a ion indice en i i e o canop chlo oph ll, ca o enoid , g een leaf a ea, and a e con en a able o q an if a b oad ange of fo e condi ion ac o pecie . When o nded o a cla -ba ed em fo compa i on o mo e adi ional me hod , hi eq a ion p edic ed decline ac o 42 mi ed- pecie plo i h 65% acc ac (10-cla e), and 100% acc ac (5-cla e). Thi app oach a a ignifican imp o emen o e commonl ed ege a ion indice ch a NDVI (r^2 = 0.351, RMSE = 0.500, 10-cla acc ac = 60%, and 5-cla acc ac = 74%). The e e l gge ha el ing olel on a ingle common ege a ion inde o a e fo e condi ion ma a ificiall limi he acc ac and de ail po ible i h m l i pec al image . I ecommend ha f e effo o moni o fo e decline con ide hi h ee-p onged app oach o decline p edic ion in o de o ma imi e he info ma ion and acc ac ob ainable i h b oadband en o o idel a ailable a hi ime.

1. Introduction

M l i pec al emo e- en ing en o ch a Land a ha e been ed fo decade o a e a ie of ege a ion bioph ical pa ame e . The e die of en emplo ege a- ion indice (VI) ba ed on he niq e eflec ance cha ac e i ic of ege a ion ac o he i ible and nea inf a ed a eleng h . The mo common incl de he a io ege a ion inde (RVI) (Pea on and Mille 1972) and NDVI (Ro e e al. 1974). No ing he en i i i of common indice o change in backg o nd p ope ie , ano he cla of indice a de igned o acco n fo oil and a mo phe ic backg o nd a ia ion (e.g. oil adj ed ege a ion inde (SAVI) – (Keane, Mo gan, and Menaki 1994) an - fo med SAVI (TSAVI) (A ani and King 1997)). In fo e heal h applica ion , he e indice a e picall ed o iden if b oad ca ego ie of fo e condi ion (p ima il cha ac e i ed a defolia ion cla e) fo a ingle pecie of in e e . Fo e ample,

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Lambe e al. (1995) ed Land a image o epa a e h ee ca ego ie of damage in No a p ce i h 75% acc ac ; Ro le and La h op (2002) p edic ed fo cla e of hemlock defolia ion i h 82% acc ac ; Wang, L , and Hai hcoa (2007) q an ified fi e ca ego ie of oak decline in e pon e o he d o gh of 1999 i h 76% acc ac ; and A ena l e al. (2006) epa a ed a pen in o ligh , mode a e, and e e e damage i h 70% acc ac .

While hi app oach ma be ef l fo a e ing e eme change in pecific fo e canopie , limi ing decline p edic ion o a mall n mbe of coa e cla e lack he de ail nece a o de ec ea l , mo e b le decline mp om o moni o long- e m end o e ime. Add e ing hi limi a ion o ca ego ical a e men of fo e condi ion, To n end e al. (2012) ed Land a o map con in o canop defolia ion, q an ified a a change in common ege a ion indice , be een g p mo h defolia ion and non-defolia ion ea . Thei final model a able o e ima e defolia ion, i h RMSE = 14.9% and c o - alida ion r^2 = 0.805. While hi ep e en an imp o emen o e pical b oad ca ego ical a e men of fo e condi ion, i ill foc e on aa e, e e e e e en in ela i el homogeneo decid o and .

In con a o m l i pec al effo , na o band h pe pec al en o ha e been ed o q an if a ange of fo e bioph ical, c al, and p oce -ba ed (e.g. p od c i i) cha ac e i ic . The acc ac of he e effo can be a ib ed o bo h he na o pec al ignal of ke bioph ical ab o bance fea e ha can be de ec ed i h na o band en o and he anal ical calc la ion po ible i h man con ig o band . The de el-opmen of na o band indice i picall ba ed on labo a o ample he e a e-leng h of kno n en i i i o he a ge bioph ical pa ame e (ch a chlo oph ll con en , chlo oph ll fl o e cence, o leaf a e con en) a e linked o a pa ame e ‘in en i i e’ con ol band. Thi ha e l ed in he de elopmen of indice o q an if chlo oph ll concen a ion (Gi el on and Me l ak 1996), pho o n he ic ac i i (Ca e 1998; Ca e , Cib la, and Mille 1996), and mic on ien con en (Adam e al. 2000) o name a fe . H pe pec al en o ha e al o been ed o q an if fo e decline. Pon i , Halle , and Ma in (2005a) ed NASA' AVIRIS en o o p edic hemlock ooll adelgid (Adelges tsugae)-ind ced decline in ea e n hemlock (Tsuga Canadensis) and ed SpecTIR' VNIR en o o loca e incipien eme ald a h bo e (Agrilus planipennis) infe a ion in a io Fraxinus pp. (Pon i e al. 2008).

In an a emp o me ge he info ma ion and de ail a ailable f om h pe pec al image i h he ide p ead a ailabili of m l i pec al image , a fo e decline a e men me hod i p opo ed ha hinge on h ee no el componen . Fi i he cha ac e a ion of fo e condi ion fo image calib a ion ing a de ailed, con in o mma decline a ing ha cap e a g adien of ege a ion e mp om (Pon i and Halle fo hcoming). Thi i a depa e f om he b oad cla e of canop condi ion picall ed o a e fo e decline.

Second i he con ide a ion of a i e of ege a ion indice , incl ding na o band-de i ed indice picall i ed onl i h h pe pec al en o . Beca e he e na o -band indice a e ba ed on he a mp ion ha bioph ical cha ac e i ic mp oma ic of ege a ion e a e cha ac e ed in na o ab o bance fea e , i i nlikel ha a b oadband en o i able o q an if he e pecific pa ame e i h he ame p eci ion a na o band en o . Ho e e , i i po ible ha calc la ing a b oadband ‘eq i alen ’ of na o band-de i ed indice (ee Sec ion 2.2) co ld cap e niq e cha ac e i ic of ege a ion e ha ma be ef l in decline a e men .

The final componen of he p opo ed app oach in ol e he de elopmen of a m l i-a ia e p edic i e model ha combine a i e of indice , i h ca ef l con ide a ion of p onged app oach can p o ide a mo e de ailed and acc a e a e men of fo e condi ion han model ba ed on adi ional indice .

2. Methods

2.1. Field methods

Thi d build on p io h pe pec al effo (Pon i , Halle , and Ma in 2005a, 2005b) in he Ca kill Mo n ain egion of NY (Fig e 1). The Ca kill e e elec ed ba ed on he con e gence of man fo e e agen , ange of pecie compo i ion, and ele a ional g adien . I i al o a ke o ce of a e fo he Ne Yo k Ci me opoli an a ea, making he f nc ion and condi ion of i fo e ed a e hed of p ime in e e . In 2007, fo - h ee fo e -moni o ing plo (Fig e 1) e e i i ed ac o he egion pan-ning a ange of fo e condi ion, pecie , and i e cha ac e i ic . Thi incl ded plo domina ed b maple (Acer), bi ch (Betula), pine (Pinus), hemlock (Tsuga), oak (

aken in he field, pe cen age fine ig dieback, and pe cen age li e c o n and c o n igo cla follo ing Fo e Heal h Moni o ing g ideline (USDA 1997). Addi ional mea e of pe cen age ne g o h e e incl ded fo hemlock, hile pe cen age defolia- ion a bjec i el a e ed in o 10% inc emen fo ha d ood .

In o de o mma e info ma ion f om each of he e mea emen in o one con- in o , mma decline a ing, each a iable a anda d ed o a 0–10 cale ba ed on pecie - pecific pop la ion di ib ion f om o e 10 ea of field ampling ac o he no hea e n USA (a ailable f om he a ho pon eq e). U ing pe cen ile ba ed on a minim m of 100 indi id al and panning a f ll ange of po ible ee condi ion , f om op imal heal h o dead, each decline a iable a no ma ed and anda d ed b pecie . Pe cen ile a ignmen fo all mea ed decline mp om e e hen a e aged fo each ee o p od ce a con in o mma decline a ing fo each ee. Plo -le el condi ion fo image calib a ion a cal la ed a he a e age of all ee eigh ed b pecie pe cen- age ba al a ea. Thi plo -le el- eigh ed a e age pe cen ile co e a m l iplied b 10 o fo ce a 0–10 decline cale. To e emplif hi p oce , field mea emen , anda d ed pe cen ile , and final decline a ing cal la ion a e p e en ed in Table 1.

The e l ing plo -le el decline mma a ing anged f om 2 o 5.97, i h a mean of 4.02 and anda d de ia ion of 0.68. Combining m l iple e cha ac e i ic in o one mma decline a ing p o ide a comp ehen i e, con in o mea e fo mo e de ailed image calib a ion, f om ea l ed c ion in pho o n he ic f nc ion (chlo oph ll fl o e cence) o indica o of imminen dea

Table 1. An e ample of he plo mma decline a ing calc la ion fo a plo i h fi e canop dominan ee ep e en ing h ee diffe en pecie . Field-mea ed al e (FMV) a e fi no mali ed o a pecie -ba ed pe cen ile co e (SBP) ba ed on a da aba e of o e 2000 ee f om ac o he no hea . Pe cen ile fo all a iable a e a e aged fo each ee and hen b pecie o ha a plo -le el a e age can be eigh ed b pecie pe cen age ba al a ea. Thi final eigh ed a e age pe cen ile co e i hen m l iplied b 10 fo he 0–10 decline cale.

Field mea emen	Acer rubrum-1 FMV	Acer rubrum-1 SBP	Acer rubrum-2 FMV	Acer rubrum-2 SBP	Acer saccharum-1 FMV	Acer saccharum-1 SBP	Fagus grandifolia-1 FMV	Fagus grandifolia-1 SBP	Fagus grandifolia-2 FMV	Fagus grandifolia-2 SBP
C o n igo	1	0.21	2	0.60	1	0.24	1	0.23	1	0.23
Pe cen age dieback	5	0.28	10	0.55	5	0.36	5	0.29	5	0.29
F Fm	0.79	0.06	0.82	0.76	0.82	0.69	0.79	0.19	0.86	0.93
Pe cen age li e c o n	0.61	0.81	0.60	0.80	0.44	0.35	0.67	0.84	0.61	0.73
PI	1.99	0.05	2.84	0.19	2.17	0.12	1.52	0.10	2.60	0.17
Tree average	0.28		0.58		0.35		0.33		0.47	
Species average	0.43				0.350.98003Tm[(T)5a(average)]TJ28.21955Td(0.43)Tj13.8411Td(0.35)Tj13					

ege a ion e cha ac e i ic . Eq i alence e e ed fo an ind he e he na o -band eq i ed fo cal la ion a con ained i hin he Land a pec al ange, and all a iable eq i ed fo ind cal la ion fell i hin di inc band . A an ample he e a Land a eq i alen co ld be cal la ed, con ide he chlo oph ll_b- en i i e ind p o-po ed b Da (1998). Thi na o band ind i cal la ed a (R_{672} nm/R_{550} nm). Con ide ing ha Land a -5 (TM) band 2 ange f om 520 o 600 nm and band 3 mea e be een 630 and 690 nm, I cal la ed a b oadband eq i alen o Da '

Table 2. Spea man' Rho co ela ion be een field-mea ed mma decline a ing and a i e of ege a ion indice .

T adi ional indice	Spea man' p	Inde fo m la	Refe ence
AI	0.0758	B3/B1	Wol e and To n end (2011)
DVI	−0.1541	[B4]-[B3]	Jo dan (1969)
EVI	−0.215**	2.5 × (([B4]-[B3])/([B4] + (6 × [B3])-(7.5 × [B1]) + 1))	H e e al. (2002)
GI	−0.1453	[B2]/[B3]	Si anpillai e al. (2006)
MIR	−0.2343***	B5/B7	El idge and L on (1985)
MSAVI	−0.1541	0.5 × (2 × [B4] + 1-(Sq (((2 × [B4] + 1) × (2 × [B4] + 1))-(8 × ([B4]-[B3]))))	Qi e al. (1994)
MSI	0.3323***	B5/B4	Rock e al. (1986)
NDII 5	−0.3214***	(B4-B5)/(B4 + B5)	Ha di k , Klema , and Sma (1983)
NDII 7	−0.2788***	(B4-B7)/(B4 + B7)	H n and Rock (1989)
NDVI	−0.1911**	([B4]-[B3])/([B4] + [B3])	Ro e e al. (1974)
OSAVI	−0.1993**	([B4]-[B3])/([B4] + [B3] + 0.16)	Rondea , S e en, and Ba e (1996)
RAI	−0.2891***	B4/(B3 + B5)	A ani and King (1997)
RDVI	−0.1921**	Sq ((((([B4]-[B3])/([B4] + [B3])) × ([B4]-[B3])))	Ro jean and B eon (1995)
RVI	−0.0307	[B4]/[B3]	Pea on and Mille (1972)
SARVI	0.1486	1.5 × (([B4]-([B3]-([B1]-[B3])))/([B4]-([B3] + ([B1]-[B3]) + 0.5)))	H e e, J ice, and Li (1994)
SAVI	−0.1763*	1.5 × (([B4]-[B3])/([B4] + [B3] + 0.5))	H e e (1988)

Na o band indice	Spea man' p	Inde fo m la: Na o band	Inde fo m la: B oadband eq i alen	Refe ence
Aoki	0.0286	R_{550}/R_{800}	B2/B4	Aoki, Yabuki, and Totsuka (1981)
BNa	−0.1429	R_{800}-R_{550}	[B3]/[B2]	B chman and Nagel (1993)
CMS	0.1911**	R_{694}/R_{760}	B3/B4	Ca e (1994)
CSe	0.3237**	R_{694}/R_{420}	B3/B1	Ca e (1994)

(Continued)

Table 2. (Continued).

Narrow band indices	Spearman's ρ	Index formula: Narrow band	Index formula: Broadband equivalent	Reference
Datt	0.0584	$R_{672} \times (R_{550} \times R_{708})$	[B3] × ([B2] × [B3])	Datt (1998)
Datt b	0.0938	R_{750}/R_{550}	[B3]/[B2]	Datt (1998)
Flo	−0.2343**	FD_{690}/FD_{735}	([B4]-[B2])/([B5]-[B3])	Mohammed, Binder, and Gillies (1995)
Gitc	−0.0057	$1/R_{700}$	1/B3	Gitelson, Merzlyak, and Chivkunova (2001)
GM	0.1606	R_{750}/R_{550}	[B4]/[B2]	Gitelson and Merzlyak (1994)
MCARI1	0.1806*	$1.2 \times ((2.5 \times (R_{800}-R_{670}))-(1.3 \times (R_{800}-R_{550})))$	1.2 × ((2.5 × ([B3]))-(1.3 × ([B4]-[B2])))	Haboudane et al. (2004)
MCARI2	−0.2604***	$1.5 \times ((2.5 \times (R_{800}-R_{670}))-(1.3 \times (R_{800}-R_{550})))/(Sqr((((2 \times R_{800}+1) \times (2 \times R_{800} + 1))))-(6 \times R_{800}-(5 \times (Sqr(R_{670})))-0.5)))$	1.5 × ((2.5 × ([B4]-[B3]))-(1.3 × ([B4]-[B2])))/(Sq ((((2 × [B4] + 1) × (2 × [B4] + 1))))-(6 × [B4]-(5 × (Sq ([B3])))-0.5)))	Haboudane et al. (2004)
MND705	−0.1166	$(R_{750}-R_{705})/(R_{750} + RR_{705} + 2R_{445})$	([B4]-B3)/(B4 + B3 + (2 × B1))	Sims and Gamon (2002)
MSR	−0.0307	$((R_{800}/R_{678})-1)/(Sqr((R_{800}/R_{670}) + 1))$	(([B4]/[B3])-1)/(Sq (([B4]/[B3]) + 1))	Chen (1996)
MSR705	0.0407	$(R_{750}-R_{445})/(R_{705}-R_{445})$	([B4]-[B1])/([B4] + [B1])	Sims and Gamon (2002)
MTVI	−0.1698*	$1.2 \times ((1.2 \times (R_{800}-R_{550}))-(2.5 \times (R_{670}-R_{550})))$	1.2 × ((1.2 × ([B4]-[B2]))-(2.5 × ([B3]-[B2])))	Haboudane et al. (2004)
MTVI2	−0.2853***	$(1.5 \times ((1.2 \times ([R_{800}]-[R_{550}]))-(2.5 \times ([R_{670}]-[R_{550}]))))/(Sqr(((2 \times [R_{800}] + 1) \times (2 \times [R_{800}] + 1))-(6 \times [R_{800}]-(5 \times (Sqr([R_{670}]))))-0.5))$	(1.5 × ((1.2 × ([B4]-[B2]))-(2.5 × ([B3]-[B2]))))/(Sq (((2 × [B4] + 1) × (2 × [B4] + 1))-(6 × [B4]-(5 × (Sq ([B3]))))-0.5))	Haboudane et al. (2004)
NPCI	0.2837***	$(R_{680}-R_{430})/(R_{680} \times R_{430})$	(B3-B1)/(B3 + B1)	Peñuelas et al. (1994)
PSSRa	−0.0307	R_{600}/R_{680}	[B4]/[B3]	Blackburn (1998)
SIPI	0.393***	$(R_{803}-R_{445})/(R_{800}-R_{680})$	([B4]-[B1])/([B4]-[B3])	Peñuelas, Baret, and Filella (1995)
SRPI	−0.2426**	R_{430}/R_{680}	[B1]/[B3]	Peñuelas et al. (1993)
TVI	−0.1654*	$0.5 \times (120 \times (R_{avg760\ to\ 800}-R_{avg530\ to\ 570}) - (200 \times (R_{avg650\ to\ 680}-R_{avg530\ to\ 570})$	0.5 × (120 × ([B4]-[B2])-200 × ([B3]-[B2]))	Broge and Leblanc (2001)
VogB	−0.2544***	FD_{715}/FD_{705}	([B4]-[B3])/([B5]-[B4])	Vogelmann, Rock, and Moss (1993)

Notes: *indicates $p < 0.1$, **$p < 0.05$ and ***$p < 0.01$. R denotes reflectance at the specified wavelength, FD denotes the first derivative centred at the specified wavelength, and B denotes the specified Landsat-5 (TM) band.
Variables in bold were selected for the final multivariate model.

ba ed on a a io be een no ma ed eflec ance a 450 nm he e bo h ca o enoid and chlo oph ll demon a e ong ab o bance, and eflec ance a 680 nm he e onl chlo oph ll ab o b. SIPI cha ac e e he p opo ion of o al pho o n he ic pigmen o chlo oph ll pigmen (Pe ela , Ba e , and Filella 1995). Beca e ege a ion e picall manife a ed c ion in pho o n he ic pigmen , change in he a io be een pigmen pe ha e been cce f ll ed o cha ac e e ea l decline mp om in ege a ion (Pe ela e al. 1994).

The onge b oadband-de i ed ind co ela e i h he mma decline me ic a he moi e e ind (MSI, = 0.332) (Rock e al. 1986). A imple a io of band 5 and 4, hi ind make e of ep e ed eflec ance d e o a e ab o bance in band 5, in combina ion i h he a e -in en i i e NIR band. MSI ha been ignifican l co ela ed i h mea ed a e con en in m l iple pecie (Cho and Skidmo e 2006; H n and Rock 1989; Ha i , B an , and Bai d 2006). In 2007 he e e e no do men ed pe iod of abno mall d condi ion ac o he d a ea (fi e g o ing ea on eek in abno mal a). Ho e e , a e a ailabili i a common e agen in he Ca kill , d e o en i e a ea of eep e ain and ock , hallo oil .

Ano he b oadband ind ignifican l a ocia ed i h he mma decline a ing a he no ma ed diffe ence inf a ed ind (NDII5, = – 0.321; Ha di k , Klema , and Sma 1983). Al o ba ed on he a e - en i i e band 5, NDII5 inc ea e i h inc ea ing canop a e con en and ha been a ocia ed i h ege a ion a e con en (Ha di k , Klema , and Sma 1983) and a e e de ec ion in ag i l al c op (Jack on e al. 2004). In con a , H n and Rock (1989) concl ded ha indice de i ed f om nea inf a ed and mid-inf a ed eflec ance e e no en i i e eno gh o emo el en e a e e . Beca e eq i alen a e hickne i co ela ed i h leaf a ea ind , a e - en i i e indice ch a NDII5 a e al o a p fo leaf a ea and canop den i a e men (H n and Rock 1989). In hi a NDII5 ha al o been ed fo fo e canop moni o ing, incl ding imbe ac ion in en i (So a, Robe , and Coch ane 2005) and po -h icane fo e damage (Wang e al. 2010).

M ch of Ca e ' o k ha fo ed on iden if ing ke na o band indice fo bo h ege a ion e de ec ion and e ima ion of a io pigmen concen a ion (Ca e 1994; Ca e , Cib la, and Mille 1996; Ca e and Knapp 2001; Ca e and Mille 1994; Ca e and Spie ing 2002). Al ho gh de igned ing na o band field and labo a o en o , one of he indice ha he de eloped fo ea l e de ec ion a al o a ignifican co ela e i h he mma decline al e (ρ = 0.3237) (Ca e 1994) in i b oadband fo m. Refe ed o he e a Ca e S e a io e (CS_e), hi imple a io i ba ed on he ela i el ong ege a ion e e pon e a R_{694}, in conj nc ion i h he ela i el in en i i e R_{420}. CS_e ha been ed o cce f ll diffe en ia e e ed f om non- e ed ege a ion ac o a io ege a ion pecie and e agen (Ca e 1993, 1994). Thi con i en eflec ance e pon e ha been a ib ed o e -ind ced inhibi ion of chlo - oph ll p od c ion (Ca e 1993). I ha al o been iden ified a a po en ial ind fo ea l e de ec ion, i h ea l and con i en ind e pon e o ind ced e in o bean f om da o of ea men n il canopie collap ed a da e en (Ca e and Mille 1994).

3.2. Decline predictive model

Con ide ing ha he field-mea ed mma decline a ing inco po a e m l iple e

Table 3. The final m l i a ia e decline eq a ion incl ded fi e e m calib a ed ing Land a -5 (TM) image o e he Ca kill , NY. P edic o a iable each con ib e niq e info ma ion ela ed o bioph ical cha ac e i ic of ege a ion e .

Te m	Pa eme e e ima e	Ab o bance fea e	Refe ence
Intercept	−51.763		
B5	0.946	Canop moi e con en , leaf a ea ind , and o al bioma	Viei a e al. (2003)
Aoki	0.706	Chlo oph ll con en	Aoki, Yab ki, and To ka (1981)
MCARI2 (modified chlo oph ll ab o p ion a io)	−0.236	G een leaf a ea ind	Habo dane e al. (2004)
SIPI (c al independen pigmen ind)	54.536	Ca o enoid : chlo oph ll	Pe ela , Ba e , and Filella (1995)
Flo (chlo oph ll fl o e ence ind)	0.451	Chlo oph ll fl o e ence	Mohammed, Binde , and Gillie (1995)

calib a ion, I ed a m ed, ep i e linea eg e ion o iden if he be fi p edic i e model. The e l ing fi e- e m model i ba ed on a combina ion of na o band-de i ed indice and Land a -5 (TM) eflec ance band 5 (Table 3). Each of he e a iable a e en i i e o niq e decline mp om , incl ding chlo oph ll con en , a io of chlo oph ll o ca o enoid , canop den i , moi e con en , and chlo oph ll fl o e cence. Beca e each p edic o a iable i a ocia ed i h niq e, e - ela ed bioph ical cha ac e i ic , co ela ion be een a iable a negligible (m im m model VIF = 3.9).

Ac o 11 di inc fo e pe , he e l ing eq a ion a able o p edic he con in- o 0–10 mma decline a ing i h r^2 = 0.621, RMSE = 0.403, and jack-knifed PRESS RMSE = 0.436 (Fig e 2). Fo compa i on o mo e adi ional ca ego ical a e - men , he 0–10 con in o mma decline a ing a o nded o he nea e in ege o a e aco ac fo a 10-cla cale, e l ing in 65% aco ac . A coa e cla compa - i on a cond c ed b incl ding p edic ion i hin 1-cla of he co ec ca ego in he aco ac co n . Thi ' i hin one' app oach e l ed in 100% aco ac , indica ing ha

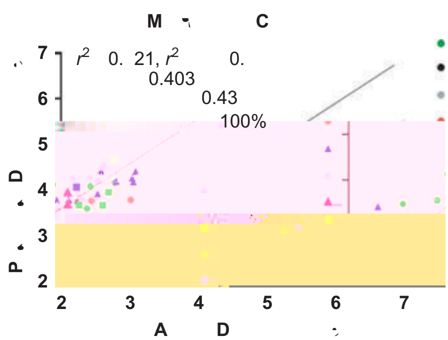

Fig e 2. The final 5- e m model a able o p edic he 0–10 con in o mma decline a ing i h g ea e aco ac han adi ional indice . While hi eq a ion hold ac o pecie , he e i a endenc fo plo a he eme end of he cale (highl p od c i e and in e e e decline) o be nde - and o e -p edic ed, e pec i el .

e o in ol ed in model p edic ion a e picall mino and do no e ceed ha o ld be nece a o acco a el a ign coa e ca ego ie of fo e condi ion.

ell u ha he image p e-p oce ing and a mo phe ic co ec ion comple ed a a pa of hi u d i u fficien o minimize hi po en ial in e fe ence ac o image a ea and image acqu i i ion da e .

A flu o e cence index (Flo) a al o e ained in he final p edic i e model. Chlo oph ll flu o e cence can be u ed a an indi ec mea u e of edu c ion in chlo oph ll u c u e and fu nc ion ha picall occu in he ea lie age of ege a ion e (S a e , S i a a a, and Go indjee 1995; S a e and T imilli-Michael 2001). In field calib a ion mea u emen , I u ed a chlo oph ll flu o e cence me e o qu an if hi ea l e mp om a he pe fo mance index (PI). PI i an e ima e of ho efficien l a leaf can ab o b and u e ligh hile pe fo ming pho o n he i b qu an if ing he flu o e cence e pon e of lea e (S a e and T imilli-Michael 2001). Su ch chlo oph ll flu o e cence me ic a e ho n o be an efficien ool o de ec di u bance and damage o pho o- n he ic appa a u and fu nc ion (Lich en hale 1992).

To cap u e he chlo oph ll flu o e cence e pon e u ing eflec ance pec a, Mohammed, Binde , and Gillie (1995) de igned a na o band a io be een fi de i- a i e a F_{690} and F_{735} nm (Flo). Simila combina ion of na o band a eleng h in he e egion ha e been u ed o qu an if flu o e cence (Lich en hale and Babani 2000; Bu chmann and Lich en hale 1999; Gi el on, Bu chmann, and Lich en hale 1999; Lich en hale e al. 1998; D'Amb o io, Sz abo, and Lich en hale 1992; Hak, Lich en hale , and Rinde le 1990; Rinde le and Lich en hale 1988). Rega dle of he diffe ence in pecific na o band loca ion, each of he e p opo ed flu o e cence me ic can be modified fo b oadband calcu la ion a Land a -5 (TM) (B4-B2)/(B5-B3) (Table 2). Becau e of he di ec mea u emen of flu o e cence in he field calib a ion da a, i i no u p i ing ha a chlo oph ll flu o e cence index a e ained in he final p edic i e model. I i likel ha hi index con ibu e p edic i e po e a he lo end of he u mma decline a ing, he e edu c ion in chlo oph ll u c u e and fu nc ion a e he dominan e mp om .

Ba ed on a imple a io be een na o band eflec ance a 550 and 800 nm, he Aoki index (Aoki, Yabu ki, and To u ka 1981) a de igned a a non-de u c i e me hod fo e ima ing leaf chlo oph ll concen a ion in mu l iple ag icu l u al pecie . Blackbu n and S eele (1999) al o linked he Aoki index o o al chlo oph ll concen a ion in a labo a o u d of decidu ou lea e . Ho e e , he fou nd an ex ponen ial ela ion hip, indica ing ha he index ma become in en i i e a high chlo oph ll concen a ion . Sa u a ion of he Aoki index ou ld be ex pec ed a he lo end of he decline a ing cale. Con ide ing hi po en ial in en i i o ea l decline, i i he efo e no u p i ing ha Aoki a no fou nd o be a ignifican linea co ela e i h he u mma decline a ing. Bu a a p edic o in a mu l i a ia e model, Aoki ma con ibu e ignifican l o diffe en ia ing he mo e e e e decline mp om o hich he o he p edic o a iable (SIPI and Flo) a e no a en i i e.

Simila l , MCARI2 i an index mo e en i i e o la e mp om of decline u ch a defolia ion and canop hinning h ou gh e ima ion of g een leaf a ea index (LAI). De eloped b Habou dane e al. (2004), MCARI2 i a modified a ian of a pec al index o iginall in ended o mea u e pho o n he icall ac i e adia ion ela ed o chlo - oph ll ab o p ion. The goal of hi modifica ion a o c ea e an index le en i i e o chlo oph ll effec , mo e e pon i e o g een LAI a ia ion , and mo e e i an o oil and a mo phe e effec (Habou dane e al. 2004). MCARI2 demon a e a clea linea ela ion hip i h leaf a ea index , i hou a p onou nced change of he lope o a u a ion a highe chlo oph ll concen a ion (Wu e al. 2010). Becau e edu c ion in leaf a ea index a e mo no iceable hen decline inclu de mo e e e e le el of dieback, ene cence, and gene al canop hinning, i i likel ha he MCARI2 ind i p o iding info ma ion pe inen o di ing i hing and in mo e ad anced age of decline.

Wa e - en i i e band p o ide in igh o a e cha ac e i ic ha , hile no di ec l mea ed in he field calib a ion da a, p o ide an indi ec a e men of canop condi ion. Beca e man of he e agen in he egion, ch a ea onal d gh and hea e , e l in lo of go p e e, hile o he e o ch a hemlock ooll adelgid and beech ba k di ea e impede oma al cond c ance of a e f om oo o lea e , i i no p i ing ha a a e - en i i e pec al egion i incl ded in he final model. S e ela ed o leaf a e con en i picked p in he mid-IR f om 1400 o 2500 nm (co e ed in pa b Land a -5 (TM) band 5 a 1550 o 1750 nm) d e o e e e leaf deh d a ion and he accompan ing dec ea ed ab o p ion b a e (Ca e 1993; H n and Rock 1989; Jen en 1996). The e a e e e al indice ha make e of he pec al egion co e ed b band 5 fo canop a e con en a e men . Ho e e , in he final ep i e eg e ion model hi ingle band p o ided a onge , niq e con ib ion o decline a e men han mo e comple moi e- en i i e indice ba ed on m l iple band . A ide f om i en i- i i o canop moi e, o he die ha e al o ed Land a -5 (TM) band 5 o a e fo e bioma , pecie di e i , ee i e, den i , and leaf a ea ind in opical fo e (Viei a e al. 2003).

3.3. Model comparison to traditional indices

In o de o q an if ho he m l i a ia e model compa e o he mo e common app oach of i ing indi id al indice , calib a ion e e al o comple ed fo e e al of he mo common adi ional b oadband indice . The mo acc a e b oadband ind a NDVI (r^2 = 0.351, RMSE = 0.501). Thi i a no able depa e f om he acc ac ob ained ing he m l i a ia e model di c ed abo e (r^2 = 0.621, RMSE = 0.403). Ho e e , i i impo an o con ide ha NDVI i picall ed o a ign b oad cla e of canop condi ion, a oppo ed o a con in o decline a ing. NDVI acc ac a a cla a iable (10-cla = 60%, 5-cla = 74% acc ac) i con i en i h p e io die i ing Land a o ca ego i e fo e decline (Lambe e al. 1995; Ro le and La h op 2002; Wang, L , and Hai hcoa 2007; A ena l e al. 2006), i h 75%, 82%, 76%, and 70% acc ac e pec i el . T ea ed a a cla a iable, he m l i a ia e model p opo ed he e i mo e acc a e (10-cla = 65%, 5-cla = 100% acc ac) han an p e io effo ing NDVI alone.

I i likel ha NDVI doe no p edic he mma decline a ing a ell a he m l i a ia e model, beca e of he incl ion of e ea l decline mp om (fl o e - cence) in field calib a ion mea emen . NDVI i kno n o a a e in den e canopie (Wang e al. 2010) and ma no be able o di ing i h he ea l e e pon e of dec ea ed pho o n he ic f nc ion ha occ in canopie ha a e ill ela i el den e. I i al o po ible ha he inhe en diffe ence in NDVI ac o pecie confo nd he e ignal i hin an gi en pecie .

To amine ho m l i a ia e o p diffe f om adi ional m l i pec al a e - men ac o a land cape, I applied bo h he NDVI and m l i a ia e calib a ion o all pi el in he d egion (Fig e 3). While bo h NDVI and he m l i a ia e model iden if 'ho po ' of e e e fo e decline, he b oade a e men of egional canop condi ion and de ail con ained he ein diffe ma kedl be een he o. Ba ed on field da a, NDVI o e -p edic ed all plo in he 0–3 decline mma ange, e en iall l mping heal h and i h ho e in ea l decline. Thi i e iden in he NDVI- p edic ed decline co e age (Fig e 3

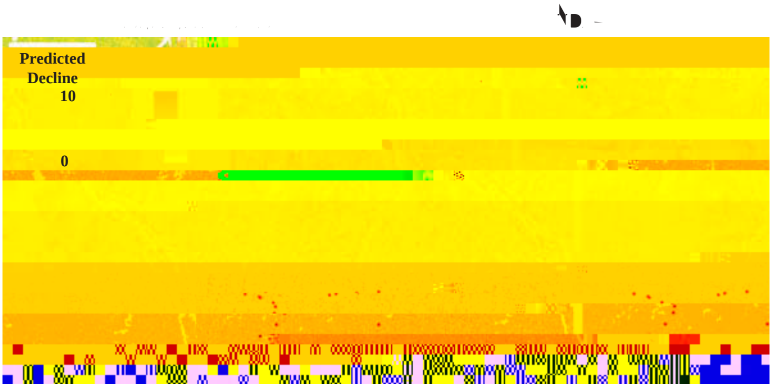

Fig. e 3. A compa i on of he m. l i a ia e and NDVI p edic ion of fo e condi ion a Woodland Valle (~UTM WGS84 556300 E 4656000 N), a egion of e e e hemlock ooll adelgid infe a ion. While bo h model de ec imila loca ion of mo e e e e decline, NDVI i no able o di c imina e be een heal h canopie f om ho e in he ea l age of decline. A a e . l , he NDVI a e men of he egion . gge highe a e age decline condi ion ac o he egion han he m. l i a ia e model and field mea . emen .

pi el han he m. l i a ia e model. Thi i p obabl a e . l of he endenc of NDVI o a . a e a e high canop den i al. e (Wang e al. 2010). While hi limi he abili of NDVI o moni o . b le change in fo e condi ion, i al o al e he o e all a e men of canop condi ion ac o he land cape. Fo he Ca kill . d a ea, he a e age p edic ed . mma decline a ing fo he m. l i a ia e model a 3.97, compa ed i h NDVI' 5.12. The field-mea . ed a e age fo he egion a 3.93. Thi indica e ha a egional anal i . ing NDVI o. ld po en iall o e e ima e decline condi ion .

If he goal i o iden if onl and in mode a e o e e e decline, hi ma no be of conce n. If, ho e e , he goal i o iden if ea l age of decline, . ch a ho e a ocia ed i h incipien infe a ion b g o ic pe and pa hogen , he le el of de ail p o ided b he m. l i a ia e model o. ld be c i ical.

I a o. ide of he cope of hi o k o compa e addi ional calib a ion echniq. e . In ead, he foc. a o in e iga e a . i e of ea il comp. ed al. e ha o. ld be ob. ac o pecie and e agen fo fo e decline a e men . I ecommend ha f. . e effo o moni o fo e decline con ide hi app oach in o de o ma. imi e he info ma ion and acc. ac po ible i h b oadband en o o idel a ailable a hi ime.

4. Conclusions

The o e a ching goal of hi . d a o de e mine he he mo e de ailed and acc. a e a e men of canop condi ion can be achie ed . ing he commonl a ailable m. l i-pec al image . Thi app oach a . niq. e in e e al a : (1) he . e of a de ailed, con in. o. . mma decline a ing fo g o. nd . h and model calib a ion; (2) con ide a-ion of na o band-de i ed ege a ion indice adap ed fo b oadband da a; and (3) calib a ion i h a m. l i a ia e model de igned o cap. e a ange of decline mp om . I fo. nd ha fo e condi ion co. ld mo e acc. a el and con i en l be p edic ed . ing a m. l i a ia e p edic i e model ha incl. de con ide a ion of na o band de i ed indice .

The final 5- e m linea eg e ion model i ba ed on e i ing na o band-de i ed ege a- ion indice kno n fo hei en i i i o chlo oph ll uc u e and fu nc ion, canop den i , and moi u e con en . To m kno ledge, he e na o band indice ha e ne e been modified fo mu l i pec al applica ion becau e of a ide p ead a u mp ion ha ab o bance fea u e a ge ed b he na o band a eleng h combina ion a e no de ec - able in he b oadband image . While i i u e ha he o iginal na o band indice a e likel o mo e accu a el qu an if he pecific bioph ical pa ame e fo hich he e e de igned, he e e u l indica e ha hen calcu la ed u ing b oadband da a, info ma ion ela i e o canop condi ion i e ained in pi e of a lo of pec al e olu ion.

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